Conflicted by decarbonisation

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ABSTRACT

This paper explores capability conflicts in the deployment of decentralised energy systems and identifies the affected population. These systems have positive societal impacts in terms of sustainability and consumer empowerment, but they are not accessible to all and their deployment may increase socio-economic inequalities. The societal impacts of decentralised energy systems can be understood in terms of conflicting capabilities; for some citizens capabilities may increase, whereas for others they may decrease. While problematic, capability conflicts may not be inherent. They may only occur in certain neighbourhoods, for example, where both affluent and less affluent populations coexist. By understanding why these capability conflicts occur, we may be able to anticipate whether these decentralised energy projects could result in societal problems. We use agent-based modelling and the scenario discovery technique to identify capability conflicts and the populations that may be affected. We distinguish five classes of conflicts, which can be used to anticipate social acceptance issues. Affected populations can be involved in the decision-making process to foster acceptance of decentralised energy systems. This work contributes to the growing political and scientific debate on issues of energy justice and inclusiveness related to the energy transition. Additionally, we contribute to the operationalisation of such capabilities, as this is one of the first papers to formalise the Capability Approach using an agent-based model.

1. Introduction

Decentralised energy systems have positive and negative impacts on societal well-being. Decentralised energy systems are energy installations that are installed close to the consumption site and aim to meet local energy needs [1]. Examples of decentralised energy systems include household solar panels, micro-grids, local energy communities and district heating systems [2]. The benefits of these systems include consumer sustainability and autonomy [3]. Renewable energy sources or waste energy are typically used for energy generation [4]. Brisbois [5] explains how the emergence of decentralised energy systems, whether controlled by individuals, communities or cooperatives, alters the political power of traditional energy companies. There are however concerns that these systems could increase socio-economic inequalities. For example, decentralised energy supply tends to be expensive and is therefore not accessible for all [6]. Those who can afford to purchase it may be able to make savings, as this can be a cheaper option than the energy supplied from traditional energy providers. Also, the quality of traditional communal energy supply and services might decrease as more affluent populations opt for decentralised forms of energy production [7]. Ultimately, the deployment of decentralised energy systems may generate societal tensions such as citizen protests and a growing mistrust of governmental institutions. The 'yellow vests' movement in France is an example of how the deployment of energy transition measures may eventually lead to social discontent [8]. These tensions may jeopardise the successful deployment of decentralised energy systems and the achievement of sustainability targets.

Positive and negative impacts of decentralised energy systems on well-being can be understood in terms of context- and system specific conflicting capabilities. Capabilities refer to “opportunities to achieve (...) 'beings' and 'doings'” [9]. Examples include the ability to live a healthy life, to have attachments to other human beings and to decide

Abbreviations: ABM, Agent-based Modelling; ECF, Environmental Conversion Factors; EMA, Exploratory Modelling and Analysis; PCF, Personal Conversion Factors; PRIM, Patient Rule Induction Method; SCF, Social Conversion Factors

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upon one's life [10]. The fulfilment of capabilities supports at least a 'partial and minimal account of social justice' [10]. From a design perspective, the difficulty is that multiple capabilities may be in conflict. Hence, it may not be possible to fulfil all capabilities at the same time. This is also referred to as 'capability conflicts' [11]. Capability conflicts may have moral consequences. For example, the deployment of decentralised energy systems may both enable individuals to increase their control over their energy consumption (i.e. capability: *Control*) and exclude others who are unable to access these technologies (i.e. capability: *Affiliation*). Capabilities may conflict, but only in specific circumstances. For example, a conflict between the capabilities of *Control* and *Affiliation* may only occur when a share of the population does not have sufficient income or suitable housing to participate in these energy systems. Identifying the circumstances in which capabilities conflict is essential for understanding potential moral issues that may occur in different types of neighbourhoods and for anticipating possible resulting issues of social acceptance (see [12,13]).

This paper aims to identify conflicting capabilities in the deployment of decentralised energy systems and who are affected by them. This is done using an exploratory modelling approach. We develop an agent-based model [14] to simulate the effect of different neighbourhoods on the occurrence of capability conflicts. Scenario discovery [15] is used to classify in which types of neighbourhoods (combinations of model input parameters) capability conflicts occur. This work contributes to the conceptualisation of capabilities. To the best of our knowledge this is the first time that the Capability Approach has been formalised into an agent-based model. This work is also in line with the core tenets of energy justice: identify injustice, identify the affected population and create an appropriate decision-making process [16].

This paper is structured as follows. Section 2 discusses the literature on decentralised energy systems and explains why the occurrence of capability conflicts is difficult to anticipate. Section 3 introduces the methods used to identify capability conflicts: agent-based modelling and scenario discovery. Section 4 describes the conceptualisation of capabilities, the resulting model, assumptions on which it is based and the experimental setup. Section 5 presents the model results and identifies five classes of conflicts and the populations that are affected by these conflicts. Section 6 discusses the model results and the implications for the technology and regulatory design of various types of decentralised energy systems. The contributions of this work, limitations and suggestions for future work are also addressed in this section.

2. Theory

2.1. Decentralised energy systems

Decentralised energy systems are forms of electricity or heat supply placed close to their point of consumption [17,18]. Walker and Cass [19] identify four degrees of spatiality for the implementation of energy systems: macro, meso, micro and pico levels. The macro level refers to centralised energy systems. Decentralised energy systems cover all levels from meso (areas) to micro (buildings) and pico (devices). They are typically formed by a set of hardware (production, storage and network technologies) and software (energy management schemes) [3,20,21]. Examples of technologies include solar water heating, solar photovoltaics, micro-wind and micro-CHP [22]. Decentralised energy systems may remain connected to the national energy grid or used as stand-alone systems [17]. Two main forms of ownership exist: individual and community ownership. An individual owner is often referred to as a 'prosumer' [23]. Energy communities are typically initiated by a group of individuals within a specific local geographical location [24]. A wider range of actors (i.e. private, public, public-private and civic actors) may be involved to carry out these projects [18,25].

The benefits of decentralised energy systems for users include sustainability, empowerment, education, affiliation and autonomy. These systems contribute to a more carbon-neutral energy mix [22,26,27] as they often involve the use of renewables. They also support the use of democratic innovation and decision-making processes [28,29]. Decentralised energy systems also provide opportunities for users to learn about energy supply and its societal impact [30]. Their deployment requires the creation of solutions that are adapted to local contexts, for example housing characteristics and living patterns of involved citizens [27,31]. They also have benefits in terms of affiliation and trust within a community. This is referred to as 'social capital' [32]. Hence, they foster social interactions between residents as well as a sense of identity [18,29,33,34]. Finally, decentralised energy systems enable users to be more autonomous in case of grid failure [21,35].

The drawbacks of decentralised energy systems include the injustices that may be generated by their deployment. Most justice and fairness issues related to decentralised energy systems discussed in the scientific literature refer to distribution of costs and benefits among community participants (e.g. [26,36,37]). Few studies have addressed injustices for populations who are not able or not willing to participate in such developments. Purchasing decentralised energy systems (individually or in communities) typically requires high upfront payments and a certain level of understanding of technologies [6]. Also, the installation of these systems is more difficult (insufficient space) or even impossible if housing is not owned but rented. Low-income and less educated societal groups may well be excluded from owning decentralised energy systems. Additionally, as more affluent households move towards decentralised energy production, the quality of traditional energy supply and services might decrease [7,38]. This could increase the vulnerability of less affluent households [39]. Finally, the deployment of decentralised energy systems is often supported by public subsidies and other forms of support mechanisms paid by all. This includes less affluent households. Concluding, the deployment of decentralised energy systems may thus contribute to a transfer of wealth from low to high income populations [7,40].

2.2. Capability conflicts

We employ the Capability Approach of Sen [41] and Nussbaum [42] as a value theory that points to different (possibly conflicting) aspects of human well-being. The Capability Approach is a conceptual framework used to assess individual well-being and evaluate social arrangements and design policies with high social impact [9]. It states that 'the freedom to achieve well-being is of primary moral importance' and the 'freedom to achieve well-being is to be understood in terms of people's capabilities' [9]. Nussbaum [10] suggests ten basic capabilities, ranging from *Bodily health* to *Emotions, Affiliation* and *Control over one's environment*. A 'partial and minimal account of social justice' [10] is provided when any of these capabilities are fulfilled above a certain threshold. The Capability Approach has been applied in developing countries but is now increasingly used in western countries too. Examples include the assessment of energy poverty and justice in Europe (e.g. [43] and [44]). Nussbaum's capabilities have been illustrated in the context of energy systems by Hillerbrand and Goldammer [45]. Table 1 provides an overview of these capabilities. This list of capabilities will be used to conceptualise the model in Section 4.2.2.

Besides providing a range of energy capabilities, the Capability Approach is used in this work to identify the factors leading to the occurrence of different conflicts. Central to this approach is the acknowledgement of human diversity. Whether capabilities are fulfilled for individuals depend both on the resources they have (e.g. income) and the conversion factors that they have to convert resources in capabilities [41]. Three types of conversion factors exist: personal (e.g. education), social (e.g. social norms) and environmental (e.g. housing properties). These factors affect the fulfilment of capabilities, but also the occurrence of capability conflicts. In the case of decentralised energy systems, forming a local energy community allows neighbours to gain autonomy (*Control over one's environment*) in comparison to

Table 1
Energy capabilities (adapted from Hillerbrand and Goldammer [45])

Energy capabilities	Application to energy systems
Life and bodily integrity	Ability to live free from accidents and long-term negative side-effects generated by energy systems (e.g. emissions).
Emotions	Ability to enjoy a safe and enjoyable life due to the availability of energy supply and the absence of emotional pain caused by the presence of energy infrastructures
Senses, imagination, and thought	Ability to educate oneself due to the availability of energy supply and the absence of taboos related to electricity production
Trust	Ability to live in a stable and reliable environment
Practical reason, or the imagination of goodness	Ability to consume electricity in line of ones perception of the good
Affiliation	Ability to identify with others and to share the (financial and non-financial) costs and benefits of energy supply
Ecological connectivity	Ability to live free from climate change and the direct negative impacts of energy infrastructure on nature
Play	Ability to have a more relaxed life due to the availability of energy supply and the absence of alteration of leisure space by energy infrastructure
Control over one's environment, Part A: separateness	Ability to be more self-sufficient in energy supply
Control over one's environment, Part B: strong separateness	Ability to participate and shape forms of energy supply

traditional energy supply. A sense of community can be created in the neighbourhood (*Affiliation*). Both capabilities are therefore aligned. However, forming energy communities may not be feasible for households living in impoverished neighbourhoods because they may lack the financial means or education required to form these kinds of communities. In this case, the formation of an energy community might involve higher risks in terms of finance and comfort, leading to more stress for participants. As a result, there may be a conflict between *Control* and *Emotions*.

2.3. Anticipating capability conflicts

Policy interventions, which typically require resources and commitment, might be needed to resolve capability conflicts. For example, subsidies can be used to make renewable energy technologies available to less affluent groups and offer them a higher degree of autonomy over their energy consumption. It is therefore essential to assess whether underlying moral issues may occur in a specific neighbourhood or district and whether the use of policy interventions is required. However, it is difficult to anticipate whether the properties of a neighbourhood with regard to inhabitants, housing and existing infrastructures may lead to capability conflicts. We identify two reasons why this is the case.

First, the fulfilment of capabilities may depend on a wide range of intertwined factors which might be too much to evaluate using simple human cognition. Koirala et al. [46] show that 'environmental concern, renewables acceptance, energy independence, community trust, community resistance, education, energy related education and awareness' all contribute to community energy system participation. Next to these socio-psychological factors, households may also be limited by their financial situation and whether they actually own their property. Geographical factors may also play a role with regard to *Affiliation*. In some cases, it might be the diversity of households with regard to this factor that explain the occurrence of capability conflicts. For example, only the more affluent population in a neighbourhood may be able to purchase decentralised energy systems. The more affluent group becomes more autonomous whereas the poorer group is less able to identify themselves with their neighbours. Here, the capabilities *Control* and *Affiliation* are in conflict.

Second, it is difficult for the human mind to fully comprehend all possible impacts that the realisation of some capabilities may have on the capabilities of other households. A capability conflicts with another when fulfilling one capability is at the expense of another. If some households decide to form an energy community to become more sustainable and autonomous, other households may be excluded based on their socio-economic characteristics and housing conditions. As a result, their capability of social affiliation might be affected. Also, a conflict is only real if households have no other reasonable opportunities to change their electricity supply to regain the same level of well-being. These opportunities need to be included in the analysis to be able to conclude that two capabilities are in conflict. Furthermore, the change in electricity supply to regain the same level of well-being may affect other households in new ways. To be able to anticipate capability conflicts, we require methods that can recreate the circumstances for such conflicts to occur. This can be achieved by using agent-based models and the scenario discovery technique.

3. Methods

This section introduces agent-based modelling and scenario discovery. An agent-based model is used in this work to simulate the potential occurrence of capability conflicts between households in one type of neighbourhood, for example, one in which households are highly educated or where there is a high diversity in education levels. The scenario discovery technique is used to run the agent-based model numerous times, each time for a different type of neighbourhoods (i.e. a different combination of household properties and spatial distribution of these characteristics over the population). This approach allows us to map the occurrence of capability conflicts between households in different types of neighbourhoods. The conceptualisation of the agent-based model and the experimental setup are further described in Section 4.

3.1. Agent-based modelling

We use an agent-based model [14] to evaluate the occurrence of capability conflicts between households in different neighbourhoods. A neighbourhood is defined as a specific combination of household properties and spatial distribution of these characteristics over the population. A simulation model is required due to the multiplicity of (heterogeneous) factors that can influence capability conflicts and the difficulty to understand how the fulfilment of some capabilities by certain households affects the fulfilment of capabilities of others (agency). Agent-based modelling originates from the fields of complexity and generative science [47]. These models are well suited to study systems in which heterogeneity, spatial distribution and interactions between entities impact overall system behaviour [48]. In a typical agent-based model, a set of agents is asked to pursue individual goals by performing a set of actions. This is done sequentially and repeatedly. As agents are given heterogeneous properties and their behaviours influence each other, we can observe emergent system patterns (e.g. capability conflicts) that are not directly inscribed in the model conceptualisation.

3.2. Scenario discovery

Scenario discovery is used to classify which capability conflicts between households occur in which types of neighbourhoods. Scenario discovery consists of two steps. First, Exploratory Modelling and Analysis (EMA) [49,50] is used to generate a high number of scenarios. This is done by running a simulation model (in this case the agent-based model) multiple times using different combinations of input parameters (e.g. average resources of agents, distribution of resources across the population, hence neighbourhood). Second, the set of scenarios is explored using the Patient Rule Induction Method (PRIM) [51]. This method is useful to find combinations of input parameters that have led to a certain outcome of interest (i.e. a conflict between capabilities). For example, we may find a conflict between *Affiliation* and *Control* (of energy production) in neighbourhoods where the population is highly heterogeneous in terms of resources and the degree of spatial clustering is low.

4. Model description and assumptions

This section explains the application of agent-based modelling and scenario discovery for this work. We evaluate whether the model is 'fit-for-purpose' and identify to what the requirements the model should comply (4.1). Next, we describe the model conceptualisation, the model agents, the capabilities and explain how capability conflicts are identified in the model (4.2). We then describe our experimental settings (4.3) and validate the model (4.4). Appendix A provides a model description using the ODD + D protocol [52]. The model and python code used to generate visualisations can be found online[1].

4.1. Simulation goal and requirements for model validation

The aim of the simulation experiment is to identify which capabilities could conflict in which types of neighbourhoods when decentralised energy systems are deployed. Additionally, we want to know which type of population is affected by these conflicts, both positively and negatively. Our simulation model should therefore comply to the following three requirements. First, the model should allow us to test a variety of neighbourhoods regarding household properties and their spatial distribution. Second, it should be able to measure the fulfilment of various capabilities as a result of different choices with regard to the level of decentralisation. Third, it should show the conflicts between capabilities for different types of populations. At the end of each model run, we should be able to measure whether a capability has increased for a certain population (e.g. an affluent population) but has decreased another capability for another population (e.g. a less affluent population).

We underline that the simulation goal is not to predict human or household behaviour and interaction. Rather, our simulation comprises a large number of illustrative 'what if' analyses, where we systematically examine whether an action taken by household A to increase one capability leads to the decrease of another capability for the same household or for household B. This is done for a large variety of types of neighbourhoods (different initial properties of households and distribution of properties over the population). Capability conflicts emerge from the chosen conceptualisation of capabilities (based on the illustration for energy systems provided by Hillerbrand and Goldammer [45], and households' heterogeneous characteristics.

4.2. Model conceptualisation

4.2.1. Types of neighbourhoods: agent properties and spatial distribution

The first requirement is that the model should allow us to test a variety of neighbourhoods in which capability conflicts might occur. Different neighbourhoods are characterised in this work by different combinations of household properties and spatial distribution of these properties over households.

In line with the CA, both resources and conversion factors (personal, social and environmental) play a role in determining the level of capabilities. In the model, an agent represents a household. Each agent is given a certain level of resources, a personal conversion factor (PCF) and an environmental conversion factor (ECF). These parameters are assigned to the population using a normal distribution of which the mean and standard deviation vary each model run (see Table 2). Social conversion factors (SCFs) are conceptualised as a measure of agent clustering. The higher the clustering value, the more agents with similar levels of resources, PCFs and ECFs are placed close to each other in the model. The lower the clustering value, the more random the distribution of agents over the model space. Fig. 1 shows an example of a population with high resources and one with low resources, both highly clustered. The level of resources and conversion factors of agents will eventually determine their level of capability fulfilment and the choices they make to maximise them.

4.2.2. Conceptualisation of capabilities

The second requirement is the ability to measure the fulfilment of capabilities. This selection explains the conceptualisation of capabilities in the model. As discussed in Section 2.2, Nussbaum [42] suggested ten basic capabilities. These capabilities have been illustrated in the context of energy supply by Hillerbrand and Goldammer [45]. In this work, we concentrate on capabilities that are affected by the introduction of decentralised energy systems compared to centralised energy supply. The theory however gives freedom on how to conceptualise capabilities. We have chosen a conceptualisation that fits within the illustration provided by Hillerbrand and Goldammer [45] and concentrate on exploring all possible conflicts that might occur within this conceptualisation.

Table 3 shows the six capabilities and explains their conceptualisation in the model. A more detailed conceptualisation of capabilities in the model can be found in the ODD + D description in Appendix A. Control over one's environment, Part A and B are combined into one capability.

We include six capabilities. We include *Emotions* since different forms of organisational modes may affect levels of security of supply. The insecurity of being able to access or afford electricity may lead to stress for households. This is especially a problem for less affluent populations (i.e. low income and low education). The introduction of decentralised energy systems may change the social dynamics within a neighbourhood, for example, by creating new groups among individuals and excluding others. This affects the extent to which households may consider their environment as stable and *Trustworthy*. We include *Senses, imagination and thought* since smaller scale electricity production places more responsibility on households, thereby encouraging them to increase their understanding of electricity supply and its impacts. *Affiliation* is affected since the deployment of new forms of organisational modes may change household well-being unequally, thereby impacting the extent to which households can identify with others. Decentralised energy systems allow households to be more autonomous (*Control over one's environment, Part A*). By forming energy communities, these households have the opportunity to have more influence on the way the electricity sector is shaped (*Control over one's environment, Part B*). Control over one's environment Part A and B are combined.

We exclude four capabilities. In western countries, decentralised electricity supply does not necessarily lead to more accidents or to improvements in local air quality (*Life and bodily integrity*). We assume that all households have access to electricity. Hence the benefits of electricity supply in terms of *Practical reason, or the imagination of goodness* are not affected. The deployment of a decentralised electricity

[1] *https://github.com/tristandewildt/Capability_Conflicts*

Table 2
Properties of agents

Agent properties	Distributions over the agent population
Resources	Normal distribution with a mean varying each model run between [0-10], with a standard deviation varying between 0.5 and 3. 0 is set as an absolute minimum for the level of resources of agents and 10 as absolute maximum.
Personal conversion factors (PCF)	Normal distribution with a mean varying each model run between [0-10], with a standard deviation varying between 0.5 and 3. 0 is set as an absolute minimum for the level of PCF of agents and 10 as absolute maximum.
Social conversion factors (SCF)	Spatial clustering of agents in the model. A degree of clustering can be varied from highly clustered to randomly placed. Clustering can be based on resources, on PCFs and resources and on ECFs and resources.
Environmental conversion factors (ECF)	Normal distribution with a mean varying each model run between [0-10], with a standard deviation varying between 0.5 and 3. 0 is set as an absolute minimum for the level of ECF of agents and 10 as absolute maximum.

supply does not particularly change nature at the local level (*Ecological connectivity*). Finally, leisure opportunities are not affected (*Play*).

4.2.3. Exploring the occurrence of conflicts

The third requirement is the ability to identify which conflicts occur in which types of neighbourhoods and who is affected by these conflicts. Hence, we need to identify when the increase of one capability leads to the decrease of another capability, and for which type of population. In this section, we first explain how a conflict can be observed in one model run. We then describe how we can identify the types of neighbourhoods in which two capabilities are in conflict and the affected population.

Occurrence of conflicts in one model run. In the model, agents aim to maximise the fulfilment of their own capabilities. To do so, they can associate or dissociate themselves to form smaller or larger production groups. The smaller the production group, the more decentralised its production. Agents in the model continuously evaluate the following options and their effects on their own level of capabilities: (1) switch to another production group, (2) form a new production group (i.e. produce individually) or (3) remain in the current production group. Agents choose the option that scores the highest for all capabilities, provided it is a feasible option for them (i.e. they have sufficient resources and conversion factors for this particular option). If none of the options are feasible, they choose the option that is closest to a feasible solution. The model stops when no agents are able to further maximise their level of capabilities.

The agents' level of resources and conversion factors influences their preferred level of decentralisation. For example, agents with low resources may prefer to be in a large production group to ensure a sufficient level of *Emotions* (i.e. more affordable energy due to economies of scale). This low level of resources might not allow them to produce themselves (i.e. be in an individual production group). In contrast, agents with high resources may prefer an individual or a small production group because this could increase their level of *Control*.

However, the choices of some agents with regard to a certain level of decentralisation may influence the fulfilment of capabilities of others. By moving to an individual production group, agents can increase their capability of *Control*, but this reduces the size of the initial production group to which they belonged. As a result, the level of *Emotions* of remaining agents in this group decreases, while the minimum level of resources and PCFs required to belong to this group increases. In this case, there is a conflict between *Emotions* and *Control*.

Identifying neighbourhoods where capabilities conflict and the affected population. Different distributions of properties over a set of households (i.e. the type of neighbourhood) may lead to different levels of decentralisation chosen by agents. This impacts whether a conflict between two capabilities occurs or not. The model output with low and high average resources for agents is compared in Fig. 1. The first picture for each scenario is the model visualisation at the start of the model run, the second is the visualisation after 50 iterations (ticks) of agents choosing to form and switch between production groups. The third picture for each scenario is an overview of the level of resources of agents. In each picture, one dot represents one agent. In the first and second pictures, each production group has a colour. In the first picture of each scenario, agents are divided among roughly 50 production groups. In the two second pictures, agents have formed new production groups. The number of production groups is low if the average resources of agents was initially set to low, and high if the average resources of agents was initially set to high. In the scenario with low average resources, only few agents (those with the highest resources) have formed individual production groups. Many more decided to unite in large production groups. In the scenario with high average resources, the number of individual production groups is clearly higher. The third picture for each scenario shows the initial distribution of resources among agents in each of these two model runs. The darker the dot, the higher the agent's level of resources. Since the second scenario is a neighbourhood with a high average level of resources, the third picture is darker than the one for the first scenario. As different average levels of resources influence agents' choices, a conflict that may occur in the first model run may not happen in the second and vice versa. Fig. 2 shows the evolution of the correlations between different capabilities from the start of the model run until after 50 iterations (ticks), when the agents' average level of resources is low and high, respectively. The figure shows that *Control* and *Emotions* (in brown) are in conflict in both cases. This is different for *Emotions* and *Thought* (in purple). In the scenario with low average resources, agents with a low level of resources choose low levels of decentralisation to ensure they can afford energy. Low levels of decentralisation are however less favourable to encourage individuals to think about electricity (*Thought*, see conceptualisation in 4.2.2). Hence, both capabilities are in conflict. In the scenario with high average resources, agents have high levels of resources, meaning that *Emotions* can also be fulfilled with high levels of decentralisation. Hence, both capabilities are aligned.

4.3. Experimental settings

This section presents the experimental settings used for the scenario discovery experiment. For each model run, a different combination of values of model input parameters (see Section 4.3.2) is selected using Latin Hypercube sampling [50]. After all model runs are performed, we evaluate which combination of parameters leads to the occurrence of capability conflicts and present the visualisations used to report circumstances in which capabilities conflict (see Section 4.3.3).

4.3.1. Experiment

The simulation model was run 2000 times, using a different combination of input parameters each time (see 4.3.2). Different combinations of input parameters mimic different types of neighbourhoods, for example, in terms of level of income and education. We found that performing additional model runs did not change the number or types of classes of capability conflicts. The total number of model iterations is set to 50 ticks. In almost all cases, the agents' levels of capabilities had stabilised by that point, meaning that an equilibrium was reached.

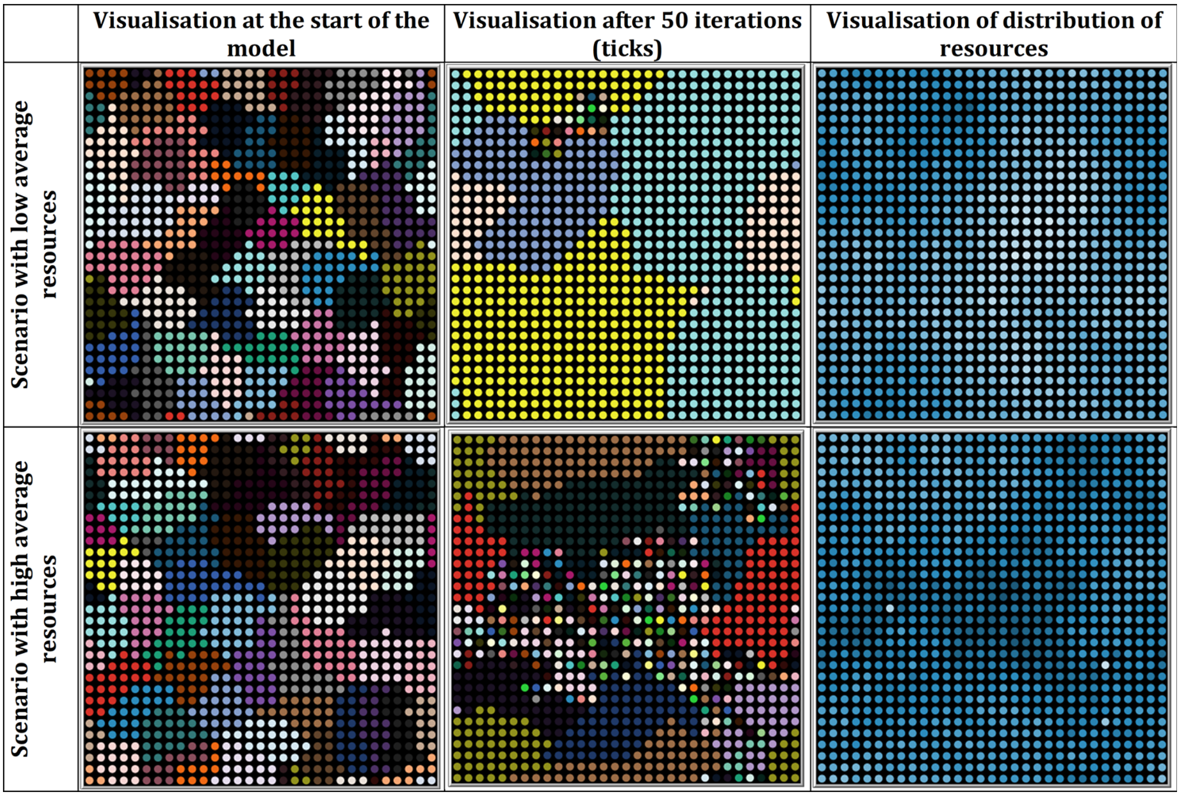

Fig. 1. Model visualisations with low and high average levels of resources of agents

Table 3
Conceptualisation of capabilities

Capabilities	Conceptualisation in the model
Emotions	A measure of the difference between the level of resources and the agents PCF, and the minimum level of resources and the PCF required to participate in a production group. If the level of resources and the PCF are insufficient, the level of Emotions is 0. The level of Emotions then increases as the distance between the level of resources and the agents PCF and the minimum required level increases.
Trust	A measure of the extent to which the size of a production group of an agent matches the size of production groups of its neighbours. The level of Trust is high if all agents are in individual production groups or if all agents are in large groups. If some agents are in small production group and their neighbours in large groups, the level of Trust of those agents will be low.
Senses, Imagination, and Thought	A measure of both the size of the production group to which the agent belongs (the smaller, the more there is to learn) and the diversity of that production group in terms of ECF (the more diverse the group in terms of housing characteristics, the more complex the required solution, and therefore the more they can learn).
Affiliation	A measure of the extent to which the level of capabilities of agents matches the level of capabilities of their neighbours. The more similar the level of capabilities, the higher the level of Affiliation (even if the level of capabilities is low).
Control over one's Environment	A measure of the size of the production group to which the agent belongs; the smaller the group, the higher the level of Control.

4.3.2. Variations of model input parameters

Table 4 presents the model input parameters and the ranges of values used to mimic different types of neighbourhoods. The *mean_resource_population* variable determines the average level of resources (e.g. average income) of the neighbourhood in a model run. A value of 8 means that the neighbourhood is predominately affluent. The *std_dev_resource_population* variable determines the standard deviation of the distribution of resources among the population. The higher this value, the more diverse agents are in terms of resources. Similar variables are created for PCFs (e.g. level of education) and for ECFs (e.g. suitable housing for decentralised energy production).

The variable *clustering_resource* determines the extent to which agents with similar levels of resources are geographically clustered. A value of 1 means that agents with similar levels of resources are placed close to each other. A value of 0 means that they are randomly distributed of the population. The variables *correlation_PCF_resource* and *correlation_ECF_resource* determine whether agents with high resources also have the highest PCFs and ECFs (i.e. they are highly educated and have suitable housing for decentralised energy production). These variables represent agents' SCFs.

4.3.3. Model outputs

We now present the visualisations used to show in which types of neighbourhoods capability conflicts between households occur and which population groups are affected. We introduce these visualisations by using the conflict between *Trust* and *Thought* as an example. Hence, following our conceptualisation of capabilities, the conflict entails that the possibility of belonging to a production group of the same size as that of the neighbours (i.e. a similar form of energy supply) is in conflict with the possibility to learn from electricity production, for oneself and for other agents.

When analysing a conflict, we first need to identify in which type of neighbourhood this conflict might occur. Fig. 3 is a PRIM visualisation (Patient Rule Induction Method, see Section 3.2) which shows the ranges of initial model parameters (the blue line) when a conflict is observed. In Fig. 3, the conflict between *Trust* and *Thought* mostly

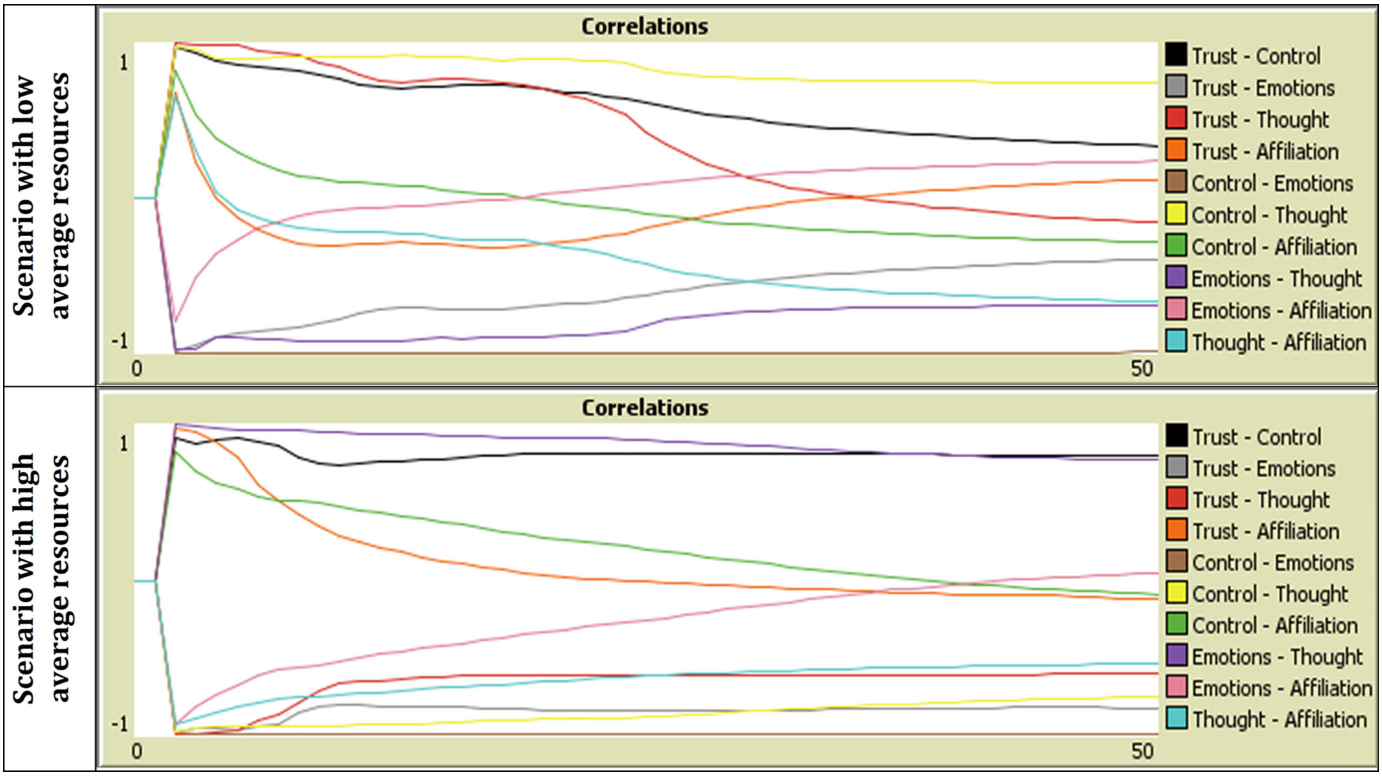

Fig. 2. Conflicts with low and high average levels of resources of agents

Table 4
Variations of model input parameters

Input parameters sweep	Description	Range
mean_resource_population	Average resource level of the entire population	[0-10]
mean_Pcf_population	Average PCF level of the entire population	[0-10]
mean_Ecf_population	Average ECF level of the entire population	[0-10]
std_dev_resource_population	Standard deviation around the mean of resources	[0.5-3]
std_dev_Pcf_population	Standard deviation around the mean of PCFs	[0.5-3]
std_dev_Ecf_population	Standard deviation around the mean of ECFs	[0.5-3]
clustering_resource	Geographical clustering based on resource levels	[0-1]
correlation_Pcf_resource	Correlation between resource and PCF level per agent	[0-1]
correlation_Ecf_resource	Correlation between resource and ECF level per agent	[0-1]

occurs when the variables *mean_Ecf_population, mean_Pcf_population, correlation_Ecf_resources, std_dev_resource_population* and *clustering_resource* are between 4.7 and 10, 4.1 and 10, 0.24 and 1, 0.75 and 3, and 0.035 and 1, respectively. We see that *Trust* is in conflict with *Thought* in neighbourhoods where houses tend to be suitable for decentralised energy production, and where agents have rather high education levels. There is also a positive correlation between agents with high resources and houses suitable for decentralised energy production. The diversity in suitability of these types of houses is also higher. As the range found for geographical clustering based on resource levels practically matches the full initial range of the input variable, this variable does not play a large role in determining the occurrence of the conflict. All other variables do not strongly contribute to the occurrence of this conflict as they do not appear in this visualisation. Second, we need to identify when a conflict between *Trust* and *Thought* occurs (i.e. which levels of decentralisation are chosen by different categories of agents leading to the occurrence of this specific conflict). This is shown in Fig. 4. The boxplot shows the categories of agents and their levels of decentralisation when *Trust* and *Thought* are in conflict. The two capabilities are in conflict when agents with high resources, PCFs and ECFs choose high levels of decentralisation. Third, we need to identify which categories of agents are affected by the conflict between *Trust* and *Thought*, either positively or negatively. Fig. 5 shows which types of agents are involved in the conflict between *Trust* and *Thought*. The diagram is divided in three sections: resources, PCFs and ECFs. Each section is divided in three groups. For example, the section resources is divided between agents with high resources, medium resources and low resources. A chord between two groups indicates that a conflict exists between these two populations. The size of a chord is a measure of how often this conflict has occurred in the total amount of model runs. The colours indicate the degree of centralisation when the conflict occurs: blue when centralised, yellow when mid-centralised and red when decentralised. Fig. 5 thus shows that the conflict between *Trust* and *Thought* is between agents with high resources and the rest of the population. The conflict is almost never between agents with medium resources and low resources. The same observations can be made with regard to PCF and ECF categories.

4.4. Model validation

We verified and validated our model using the Evaludation method described in Augusiak et al. [53]. This method comprises six steps: data

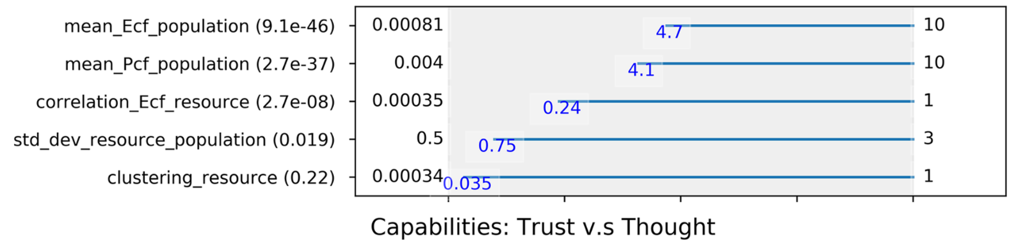

Fig. 3. PRIM visualisation showing ranges of initial model parameters leading to capability conflicts

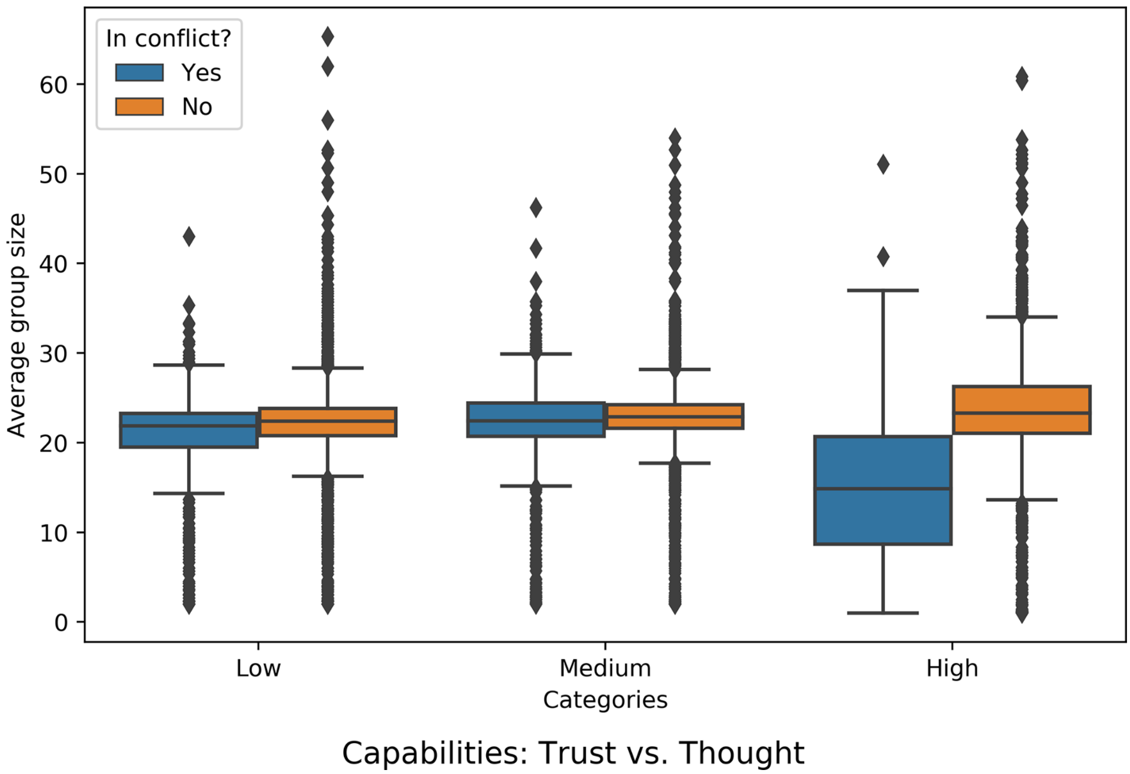

Fig. 4. Levels of decentralisation when *Trust* and *Thought* are in conflict

evaluation, conceptual model evaluation, implementation verification, model output verification, model analysis and model output corroboration.

The data is a translation of the operationalisation of the Capability Approach in the context of decentralised energy systems. We conducted sensitivity analyses to verify that variation of curve parameters did not influence our conclusions in terms of the classes of conflicts identified in Section 5. The conceptual model evaluation and model output verification steps are challenging in our case as we were unable to find other models in which the Capability Approach is conceptualised in the literature. We performed a series of logical tests to verify that the model adequately matches the core ideas of the Capability Approach, for example, that both resources and conversion factors influence the fulfilment of capabilities. We used four tests proposed by Van Dam et al. [54] for the implementation verification: recording and tracking of agent behaviour, single-agent verification, minimal model interaction verification and multi-agent verification. Model output corroboration was conducted by verifying that model outputs could be related to cases of energy injustices observed in the real world.

5. Model results

In this section, we present capability conflicts identified by means of the model and approach described in Section 4. Capability conflicts are grouped into five classes of conflicts, based on the types of neighbourhoods where they could occur and the affected population:

- Class 1: Conflicts in centralised energy systems for all populations
- Class 2: Conflicts in centralised energy systems for affluent populations
- Class 3: Conflicts in (partially) decentralised energy systems for less affluent populations
- Class 4: Conflicts when only affluent populations choose decentralised energy systems
- Class 5: Conflicts in decentralised energy systems

The five classes of conflicts are further described in Section 5.1 through Section 5.5. For each class of conflict, we present the figures of only one conflict observed in this class. This is because the circumstances leading to other conflicts in this class are similar, hence also the figures (see Appendix B). Fig. 6 visualises the five classes of conflicts where each conflict class is represented by a red line. A dot on a line indicates that this class refers to a specific population, e.g. with low resources and medium decentralisation (Class 3). The arrow side means 'the rest of the population'. Hence, a line with both a point and an arrow indicates that the conflict involves one specific group of agents and the rest of the agent population.

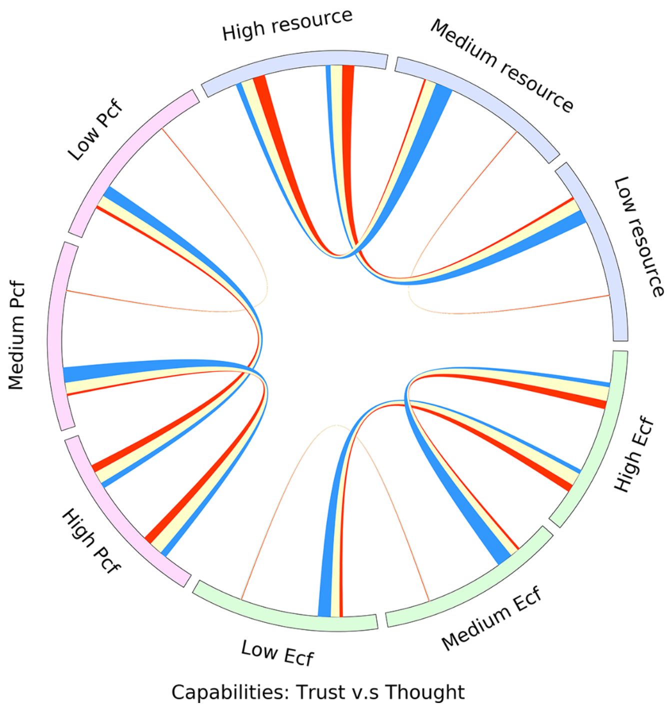

Fig. 5. Types of population groups affected by conflict between *Trust* and *Thought*

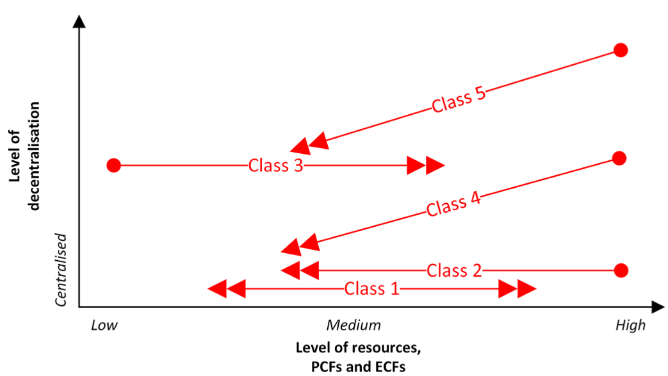

Fig. 6. Summary of classes of conflicts

5.1. Class 1: Conflicts in centralised energy systems for all populations

Fig. 7 shows that a first class of conflicts occurs when the average level of resources of the population is low to medium (see PRIM visualisation). Here, all agents choose large production groups (see boxplot). These conflicts are frequent in all model runs and between every population categories (see chord diagram). Conflicts occurring in this class are:

- *Control-Emotions*;
- *Emotions-Thought*.

The explanation is the following. In less affluent neighbourhoods, levels of income (i.e. resources) and education (i.e. PCFs) of households tend to be lower. A highly centralised system contributes to economies of scale, thereby making energy more affordable. As a result of this choice, the level of *Emotions* of households increases. However, following the conceptualisation of capabilities and the choices made here by agents, their levels of *Control* and *Thought* decrease.

5.2. Class 2: Conflicts in centralised energy systems for affluent populations

Fig. 8 shows that a second class of conflicts occurs when there is a discrepancy between resources and PCFs (high), and ECFs (low). Here, all agents choose relatively large production groups, with similar circumstances as those observed in Class 1 conflicts. They however affect populations with high levels of resources, PCFs and ECFs more. Conflicts occurring in this class are:

- *Affiliation-Control*;
- *Affiliation-Thought*;
- *Trust-Emotions*.

In neighbourhoods where houses tend to be inadequate for decentralised energy installations (i.e. low ECFs), households are forced to keep using traditional (centralised) energy supply. The problem in terms of capabilities is particularly for households with high income (i.e. resources) and education (i.e. PCFs), since they would normally tend to choose more decentralised forms of energy production. As a result, their levels of *Control* and *Trust* decrease. The overall levels of *Affiliation* and *Trust* however increase, as all populations make similar consumption choices that are also largely affordable.

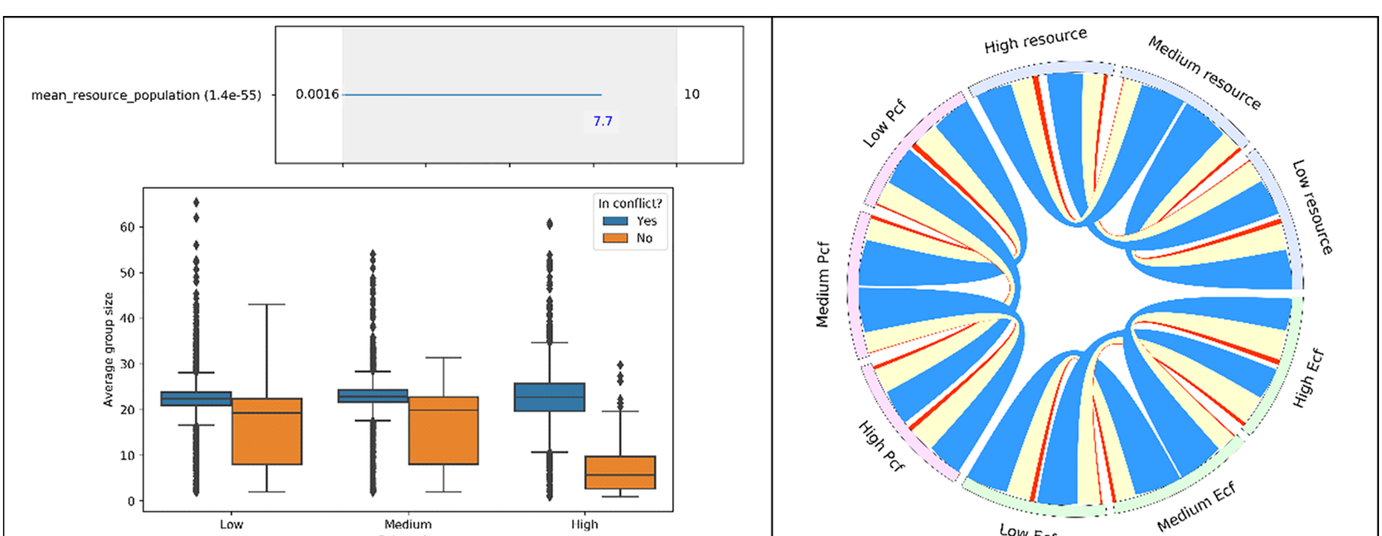

Fig. 7. Description of class 1 conflicts

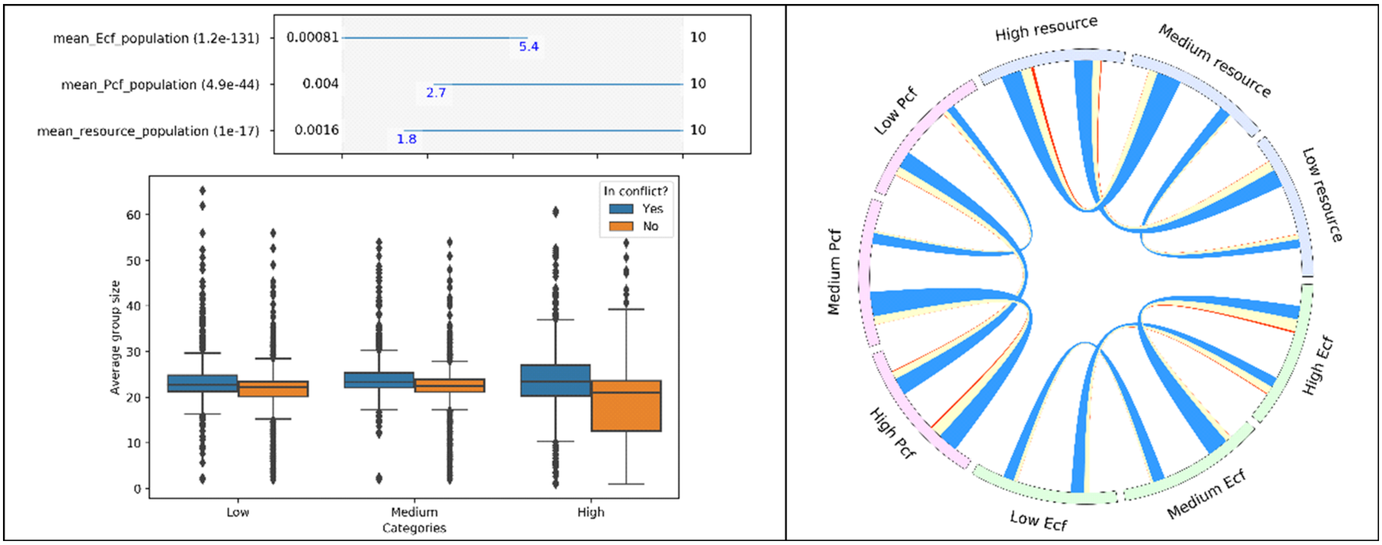

Fig. 8. Description of class 2 conflicts

5.3. Class 3: Conflicts in (partially) decentralised energy systems for less affluent populations

Fig. 9 shows that a third class of conflicts occurs when the average levels of resources and PCFs of the population are high. Here, agents tend to choose relatively medium sized production groups. These conflicts affect populations with low resources and PCFs. Conflicts occurring in this class are:

- *Affiliation-Trust*;
- *Affiliation-Affiliation*.

In relatively affluent neighbourhoods, the population is inclined to choose higher levels of decentralisation. This creates a problem for populations with lower income and education. To increase their level of *Trust*, these households would be tempted to choose decentralised means of production too. This would however come at high costs in terms of the other capabilities that they have (*Affiliation*). In these cases, while decentralisation has a positive impact on *Affiliation* for affluent populations, it has a negative impact on the *Affiliation* of the less affluent ones.

5.4. Class 4: Conflicts when only affluent populations choose decentralised energy systems

Fig. 10 shows that a fourth class of conflict occurs when the average level of PCFs and ECFs is high, and the correlation between ECF and resources is high. Here, only agents with high levels of resources choose decentralised energy production. The conflicts are between this category of agents and the rest of the population. Conflicts occurring in this class are:

- *Control-Trust*;
- *Thought-Trust*;
- *Emotions-Affiliation*.

In affluent neighbourhoods, households may end up choosing very decentralised means of energy production (i.e. produce individually). As a result, their levels of *Control* and *Thought* increase strongly. Consequently, the entire population faces a decrease of *Trust*. This is because the diversity with regard to the chosen means of energy production is large. Households are less certain that they have made the appropriate choice. The diversity of choices also has impacts in terms of

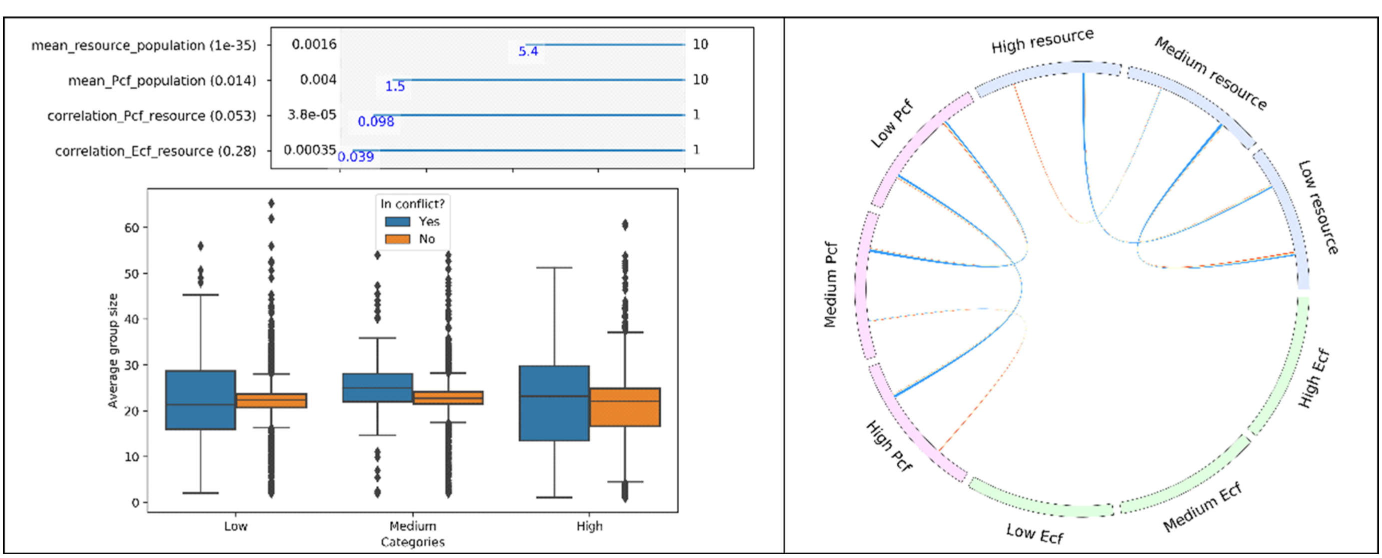

Fig. 9. Description of class 3 conflicts

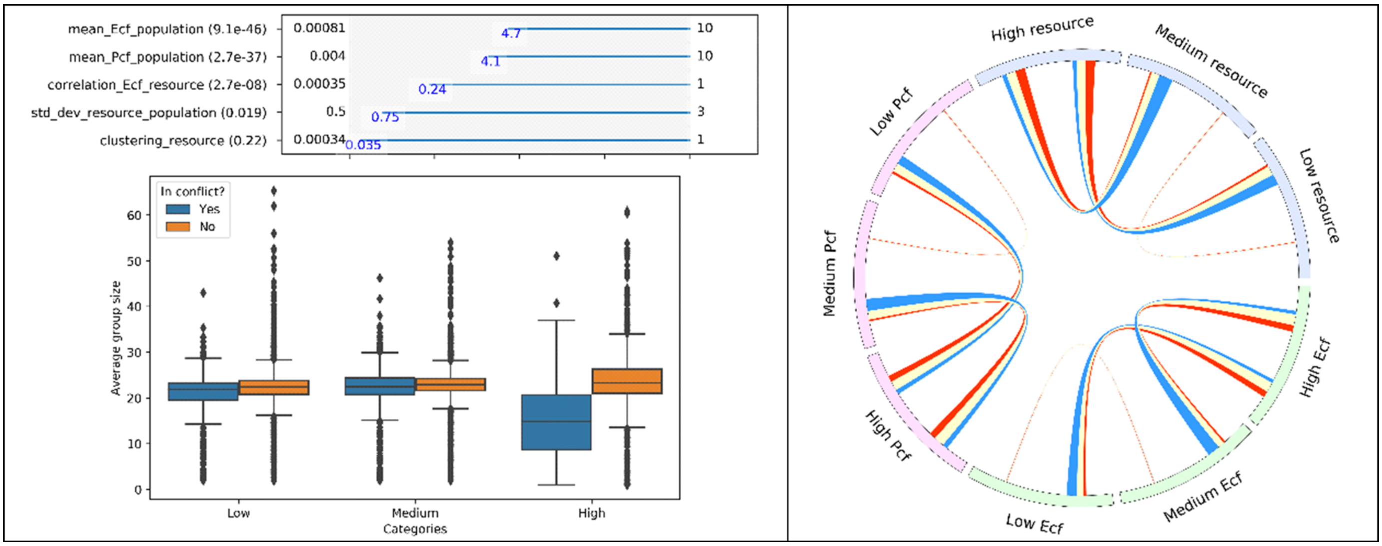

Fig. 10. Description of class 4 conflicts

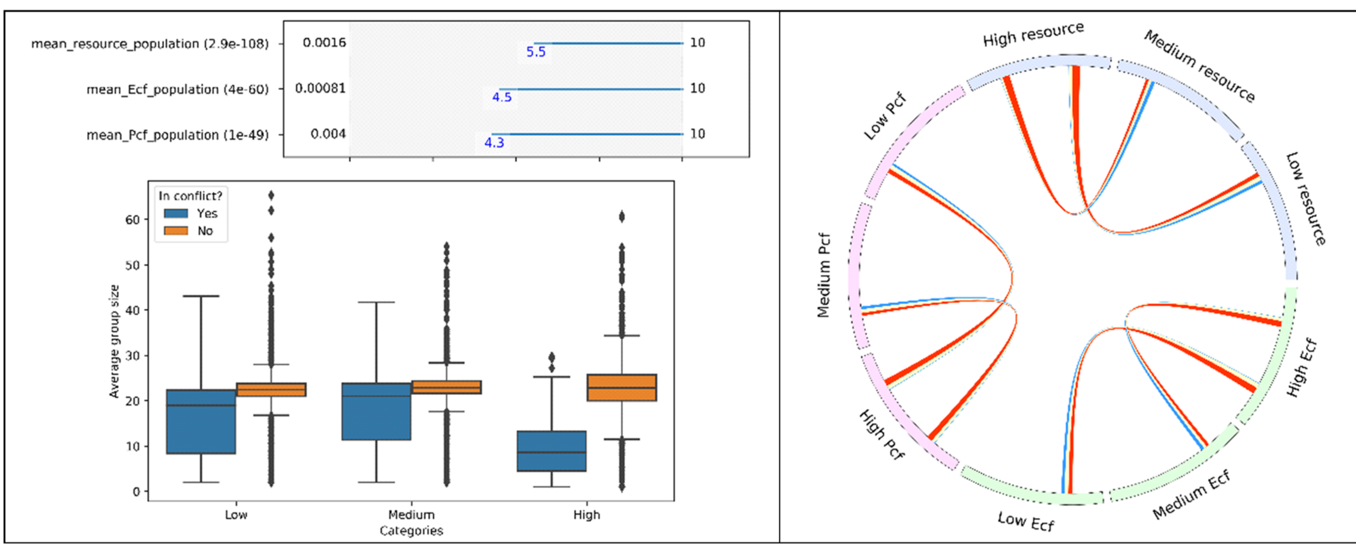

Fig. 11. Description of class 5 conflicts

Affiliation and pushes households to make decisions that may not be favourable in terms of their *Emotions*.

5.5. Class 5: Conflicts in decentralised energy systems

Fig. 11 shows that a fifth class of conflicts occurs when the average level of resources, PCFs and ECFs is very high. All agents choose rather small production groups, with agents with high resources choosing even smaller ones (i.e. individual production). These conflicts are between agents with high resources, PCFs and ECFs, and the rest of the population. Conflicts occurring in this class are:

- *Emotions-Emotions*;
- *Thought-Thought*;
- *Control-Thought*;
- *Control-Control*.

In affluent neighbourhoods, a competition for *Control* might occur. The most affluent population is typically able to produce individually and therefore gain high levels of *Thought* and *Control*. Less affluent populations might however need to rely on the first category of households to be able to establish relatively small production groups such as energy cooperatives. The possible choice of the most affluent population to produce individually has therefore negative consequences in terms of *Control* and *Thought* for the rest of the population. An advantage for the latter population is however that their level of *Emotions* increases.

6. Conclusions and discussion

6.1. Conclusions

This paper identified conflicting capabilities in the deployment of decentralised energy systems in neighbourhoods using an agent-based model and scenario discovery. Five classes of capability conflicts were identified:

- Class 1: Conflicts in centralised energy systems for all populations
- Class 2: Conflicts in centralised energy systems for affluent populations
- Class 3: Conflicts in (partially) decentralised energy systems for less affluent populations
- Class 4: Conflicts when only affluent populations choose

decentralised energy systems
- Class 5: Conflicts in decentralised energy systems for all populations

These classes of conflicts affect the social acceptance of decentralised energy systems differently. Capability conflicts can eventually result in social acceptance issues [12,13,55]. How conflicts affect a population is indicative for the types of moral problems that are created and hence the types of acceptance issues that could emerge. By analysing the five classes of conflicts, we identified three types of moral issues: those inherent to a technical or organisational choice, personal dilemmas and conflicts between population groups.

First, capability conflicts can affect all populations, independently of the characteristics of households. This can be seen in Class 1 and Class 5 conflicts. In these cases, conflicts are inherent to a technical or organisational choice. Centralised energy systems are beneficial in terms of affordability (*Emotions*), due to economies of scale. This however conflicts with consumer empowerment (*Control*). Consumers depend on the initiative of (often large) energy suppliers to have access to their preferred source of energy production (e.g. more sustainable ones). Decentralised energy systems may create a competition for *Control*. As they are not affordable for all, less affluent households are dependent on the willingness of others to engage in energy cooperatives and gain higher levels of *Control* and *Thought*. In these cases, related capability conflicts can only be solved by choosing a different form of electricity supply. This new form of electricity supply may however have capability conflicts of its own.

Second, conflicts can be specific to a type of population. This can be seen in Class 2 and Class 3 conflicts. In Class 2 conflicts, affluent populations may choose more decentralised production. This enables them to have more *Control* over their energy consumption and to learn about energy supply. From the point of view of *Affiliation*, the drawback is however that their levels of well-being will increase significantly compared to other groups. They might become more socially isolated, for example, because of jealousy between groups of citizens. In Class 3 conflicts, less affluent populations may choose to participate in more decentralised forms of energy production too. This enables them to feel more socially included. However, compared to other groups, this might negatively affect their level of well-being due to higher costs of decentralised production. Both Class 2 and Class 3 conflicts relate to some form of personal dilemma. However, in Class 3 conflicts this is triggered by the choices of other population groups.

Third, conflicts can occur between population groups. This can be seen for Class 2, 4 and 5 conflicts. In Class 2 and 4 conflicts, the fact that affluent populations choose higher levels of decentralisation will both decrease their level of *Affiliation* and *Trust*, and those of less affluent populations. In Class 5 conflicts, the fact that affluent populations choose highly decentralised production enables them to achieve a high level of *Control* over their energy production. However, a less affluent population is dependent on a more affluent population to provide sufficient levels of resources and knowledge to form decentralised production groups. By choosing highly decentralised production groups (e.g. individual production), affluent populations exclude others from the opportunity to adopt more decentralised forms of energy production. These groups can have high levels of *Control* over their electricity production and more opportunities to educate themselves, at the cost of less affluent populations.

The classes of capability conflicts identified in this work can be used to anticipate future social acceptance issues and deploy adequate policies. As suggested by Van de Poel [56], innovation could be an approach to solve value conflicts. The author explains that technical innovations can 'ease value conflict' as it 'enlarges the feasibility set'. For example, the smart electricity meter eases the tension between grid reliability and sustainability facing the deployment of intermitted renewable energy sources [57]. The challenge is thus to find innovations that can address these issues. Other approaches include cost-benefit analysis or direct trade-offs [56]. A list is also suggested by Thacher and Rein [58]. For example, organisations could share responsibility for conflicting values so that value conflicts are institutionalised as a constant tension between two or more organisations.

6.2. Implications of identified conflicts for the design of decentralised energy systems

This work contributes to the emerging scientific and political debate on inclusiveness issues generated by the energy transition. Green energy technologies offer multiple advantages, including increased consumer autonomy and sustainability. These technologies are however more accessible for affluent populations and may therefore create issues of distributive justice. This research shows that decentralised energy systems are not different in this respect. This work has three implications for the design of decentralised energy systems.

First, this work shows that the design of decentralised energy systems needs to be adjusted based on the characteristics and diversity of households that reside in the area of interest. This includes those related to their financial situation, to their housing properties, but also to more social and psychological characteristics. Specific capability conflicts only occur in certain types of neighbourhoods. Competition for *Control* (Class 5 conflicts) occurs when the population is affluent and lives in conditions that are particularly suitable for the deployment of decentralised energy systems (e.g. households have a lot of space). Regulation can be put in place to support the deployment of energy communities. However, this could fail if a affluent population can achieve energy consumption goals individually, without having to rely on neighbour participation.

Second, although no negative societal responses were perceived during the deployment phase of a decentralised energy system, this does not mean that it will be free of social acceptance issues in the future. The distinction between moral acceptability and social acceptance (see [59,60]) shows that technological and organisational choices might still bear underlying moral issues even though this might not be observed through political debates or citizen protests. The consequence of these conflicts might only appear in certain circumstances, for example, because of a change in the (implicit) societal prioritisation of capabilities (or values). Class 1 conflicts have always been an underlying issue due to past choices to concentrate on energy provision through centralised energy systems. Only later did these conflicts enter the 'societal cognitive domain', mainly due to the growing mistrust of citizens of the ability of large energy firms to make more sustainable choices. Class 3 conflicts may be a serious reason for concern. They may not be visible, now or in the future, because less affluent groups are too small in rich countries or they are not sufficiently represented by political parties. Furthermore, their impact on the well-being of less affluent populations can be severe.

Third, certain types of conflicts have more severe effects than others and might therefore need to be prioritised. Resolving capability conflicts requires resources. Hence, it is necessary to prioritise the resolution of conflicts by evaluating their potential impact. [13] suggest three factors: the severity of resulting acceptance issues, the extent to which conflicts are resolvable, and the resources required to resolve them. With this in mind, the discussion on capability thresholds is highly relevant. In her work, Nussbaum [10] argues for the specification of capability thresholds. The fulfilment of each capability above these thresholds would guarantee a minimum level of social justice. Holland [11] however states that guaranteeing social justice is a matter of trade-offs among capabilities. Therefore, establishing capability ceilings would allow us to limit the amount of resources spent on capabilities that are in conflict.

With regard to this work, the fact that capabilities are in conflict is not inherently problematic with regard to social justice. Rather, it is a problem when conflicts lead to the fulfilment of some capabilities falling under these thresholds, and when these capabilities cannot be fulfilled by other infrastructures and organisational systems as a replacement. Conflicts occurring in decentralised energy systems (Class 5 conflicts) lead to a decrease of the capability *Emotions* for affluent populations. However this conflict does not seem to be problematic as these populations tend to have sufficient resources to cope with less affordable energy. Conflicts in centralised energy systems for more affluent populations (Class 2 conflicts) are more problematic. The capabilities of *Thought* and *Control* are linked to the practice of democracy. This is critical currently, since the fulfilment of these capabilities encourages a transition to a more sustainable form of energy supply. However, *Thought* and *Control* can be fulfilled by other initiatives, for example, through new political movements. Finally, conflicts occurring in (partially) decentralised energy systems for less affluent populations (Class 3 conflicts) are critical. Here, *Affiliation* (i.e. the overall level of well-being) may significantly decrease for less affluent populations. Also, this fulfilment of this capability cannot easily be adjusted due to the amount of resources required for compensation. This class of conflicts may therefore be highly problematic with regard to the level of the social justice provided by decentralised energy systems and to potential future issues of social acceptance.

6.3. Contributions, limitations, and future work

This work aims to classify capability conflicts that might occur in the different types of neighbourhoods and to identify the type of population affected by these conflicts by using agent-based modelling and scenario discovery.

This work offers three main contributions.

1. It contributes to the ability to anticipate potential problems of social acceptance and social justice in various neighbourhoods during the deployment of decentralised energy systems. We have identified the type of population affected by these conflicts. This is essential for policy-makers to adjust the technological and regulatory design ex ante to solve potential problems that might emerge in a later stage of deployment. Also, this indicates which types of citizens and societal actors need be involved in the decision-making process to increase the chances of successful deployment.
2. It contributes to the overall debate on the inclusiveness of the energy transition. Particularly, this work is in line with the emerging literature on energy justice (see [16]). The exploration of capability conflicts contributes to distributional justice, and the identification of affected populations to recognitional justice. Both can then be used to design fairer decision-making processes.
3. It is, to our knowledge, the first in which the Capability Approach is explicitly formalised into an agent-based model. By focusing largely on the individual, the Capability Approach and agent-based models are largely compatible in a conceptual sense. We have introduced a new way in which the Capability Approach can contribute to addressing issues of inequality and well-being. We also contribute to further exploring and conceptualising the notion of capability conflicts. While recurrently acknowledged in the Capability Approach literature (e.g. [11,61,62]), the consequences of capability conflicts on the feasibility of such a conceptual framework of well-being have not yet been systematically explored.

A first limitation of this work is the application of the Capability Approach to a specific technology, in this case decentralised energy systems. Other (coexistent) systems to these technologies may play a role in the fulfilment of capabilities and as such may also solve some of the conflicts identified by the model. For example, we might question whether the need for *Control, Thought* and *Affiliation* should necessarily be solved by decentralised energy systems. Different social projects may achieve similar effects. Results from the model should therefore be interpreted by taking the wider context of energy decentralisation into account.

A second limitation is the conceptualisation of capabilities, which is highly dependent on the case modelled and specific technical and organisational details. A large range of possible conceptualisations for one capability may be valid. In this work, we have chosen to concentrate on one conceptualisation that fits within the illustration provided by Hillerbrand and Goldammer [45] and explore capability conflicts that might occur between groups, within groups and within individuals in a systematic and rich manner.

Methodologically, future work includes the application of this modelling approach to an empirical case. The use of qualitative data in the form of functions describing the relationship between resources, conversion factors and the achievement of capabilities was sufficient to identify multiple classes of capability conflicts. It may however be beneficial to evaluate model results with richer data.

Future work for the deployment of decentralised energy systems could include participatory methods to involve citizen groups affected by specific capability conflicts. A promising method is the Participatory Value Evaluation methodology [63], which could include citizens' moral considerations in the policy-making process.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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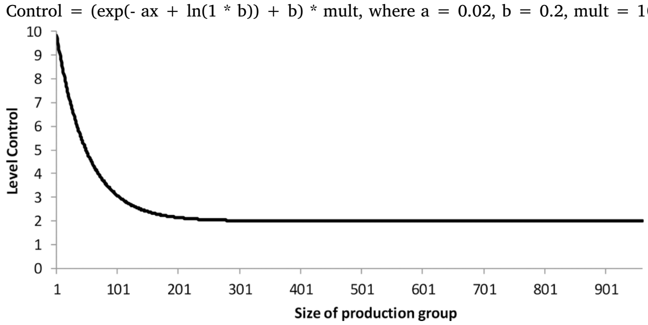
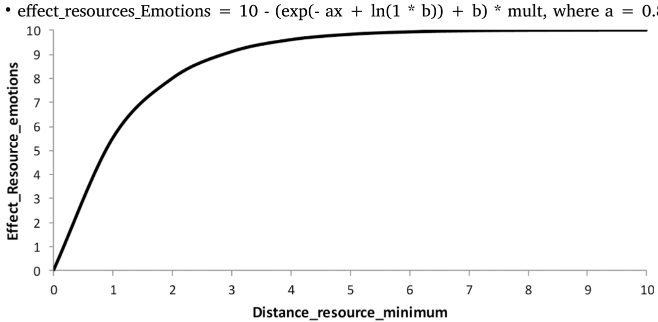
Appendix A. ODD + D model description

Overview	
Purpose	- To identify capability conflicts in socio-demographic and housing conditions for different kinds of populations.
State variables and scales	- The agents have properties of households, conceptualised based on the Capability Approach: • Resources • Personal Conversion Factors (PCFs). • Social Conversion Factors (SCFs). • Environmental Conversion Factors (ECFs). - Resources, PCFs and ECFs are values between 0 and 10. The SCF is a variable of spatial clustering of agents with similar resources, PCFs and ECFs. The value of SCF can be set between 0 and 1. A SCF of 0 means that characteristics are randomly distributed over agents. A SCF of 1 means that agents with e.g. high resources, PCFs and ECFs are placed close to each other. - The values of resources, PCFs, SCFs and ECFs of agents do not change over time in the model. Indeed, the goal is solely to identify how different levels and configurations of these characteristics impact the occurrence of capability conflicts.

Process overview and scheduling	- Setup: • The levels of resources, PCFs and ECFs are distributed over agents. • Agents are randomly placed in a number production groups. • A level of SCF (clustering of agents among properties) is set between 0 and 1. - Go: • Agents try to increase the sum of the five levels of capabilities. This is done by switching, creating new production groups, joining existing production groups or remaining in their current production groups. • The model runs until all agents have no further opportunities to increase their levels of capabilities (approx. 50 ticks).
Design concepts	
Theoretical and empirical background	- The Capability Approach [41,42]. We use two key elements from this approach: • The list of ten capabilities suggested by [42] and illustrated in the context of energy systems by [45]. We retain six capabilities, as they are most affected by the deployment of decentralised energy systems. Control part A and B are integrated into one capability. • The fulfilment of capabilities is evaluated by considering both the resources and conversion factors that individuals have in order to transform resources into capabilities.
Individual decision making	- Each ticks, agents aim to increase their overall level of capabilities (sum of all five levels of capabilities): • Capabilities are *Trust, Control, Emotions, Thought* and *Affiliation*. The level of a capability is a value between 0 and 10, 10 being a capability completely fulfilled. - Agents evaluate which of the following options increase their overall level of capabilities most: 1. Stay in the current production group. 2. Start a new production group (individual). 3. Join an neighbouring production group. - Agents calculate the best feasible option (i.e. whether their level of resources, PCFs and ECFs is sufficient for this option). - Agents choose the option that increases their overall level of capabilities most, provided that this option is feasible. If no option is feasible, they choose the most feasible option.
Learning	- None
Individual sensing	- Agents look at their surroundings at two stages: • To evaluate *Trust*, they look at the size of production groups of their direct neighbours. • To evaluate *Affiliation*, they look at the fulfilment of the other four capabilities of their direct neighbours.
Individual prediction	- None
Interaction	- There is no specific interaction in the sense that that agents ask each other information. Rather they look at the characteristics of their neighbours (see individual sensing).
Collectives	- Agents belong to energy production groups. Their sizes can vary between 1 (individual production group) to 961 agents (total of agents in the model).
Heterogeneity	- Agents are heterogeneous with regard to their levels of resources, PCFs and ECFs.
Stochasticity	- The following elements are stochastic in the model: • The initial placement of agents in production groups. • Randomised agent iteration. • Properties of agents with regard to resources, PCFs and ECFs are distributed over the population of agents with a mean and a standard deviation around that mean.
Observation	- The model provides the following output: • Level of fulfilment of each capability of agents. • Correlation between capabilities for different groups of agents (e.g. those with low, medium and high resources).
Details	
Implementation details	- The model is implemented in Netlogo. - The following functions are used: **Fulfillment of capabilities** *Trust* Trust = 1.25 - ((abs (size of production group â size of production group of neighbour) / 961) * 1.25) * number of neighbours *Control* Control = (exp(- ax + ln(1 * b)) + b) * mult, where a = 0.02, b = 0.2, mult = 10, x = size of the production group  *Emotions* Effect of level of resources on *Emotions* • Distance_resource_minimum = resource - minimum required resource

- If Distance_resource_minimum < = 0, effect_resources_Emotions = 0
- If Distance_resource_minimum > 0
- effect_resources_Emotions = 10 - (exp(- ax + ln(1 * b)) + b) * mult, where a = 0.8, b = 0, mult = 10, x = Distance_resource_minimum



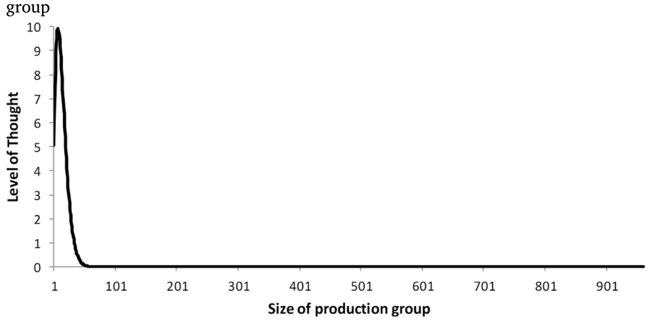
Effect of level of PCFs on *Emotions*: Similar as for resources

Level of Emotions = Min(level of Emotions for resources; level of Emotions for PCFs)

Thought

variance_Ecf_group = variance (Sum(ECF of agents in production group))

effect_of_size_community = (k / l) * (x / l)^(k - 1) * exp(-1 * (x / l)^(k)) * mult, where: k = 1.5, l = 15, mult = 200, x = size of the production group



Thought = variance_Ecf_group / 10 * effect_of_size_community

Affiliation

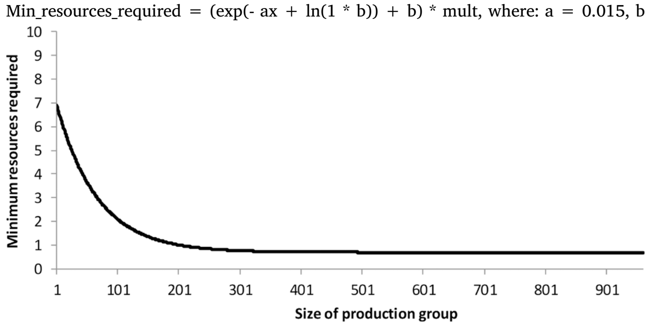
Level of affiliation gained per capability = 2.5 - ((abs (mean capability of neighbors - capability) /10) * 2.5)

Affiliation = Sum of all Level of affiliation gained per capability

Minimum level of resources, PCFs and ECFs to join a production group

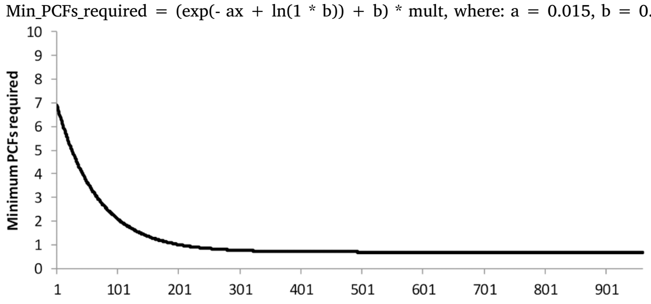
Resources

Min_resources_required = (exp(- ax + ln(1 * b)) + b) * mult, where: a = 0.015, b = 0.1, mult = 7, x = size of the production group



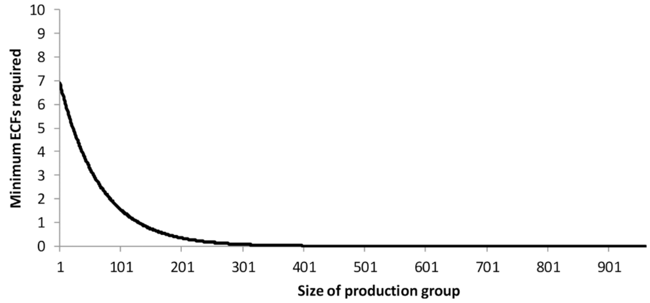
PCFs

Min_PCFs_required = (exp(- ax + ln(1 * b)) + b) * mult, where: a = 0.015, b = 0.1, mult = 7, x = size of the production group



ECFs

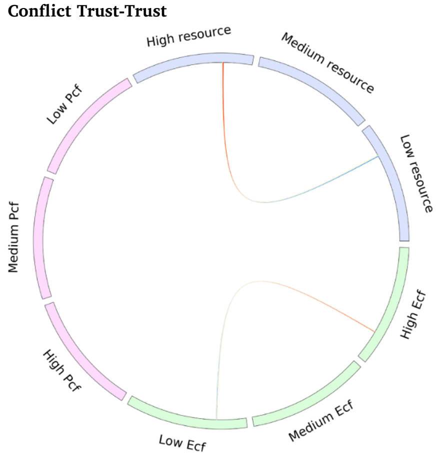
Min_ECFs_required = (exp(- ax + ln(1 * b)) + b) * mult, where: a = 0.015, b = 0.1, mult = 7, x = size of the production group



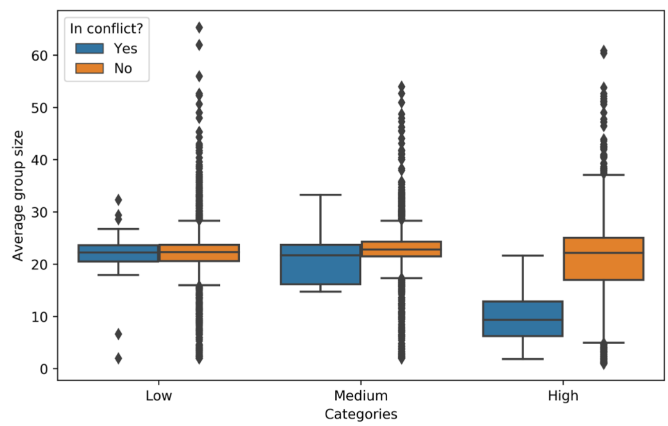
Initialization	- Agents are randomly divided into 50 production groups. - Agent properties with regard to resources, PCFs and ECFs are distributed over the population.
Input	- Distribution of resources, PCFs and ECFs over the population. - Degree of clustering of agents with similar properties with regard to resources, PCFs and ECFs over the population.
Submodels	- No submodels

Appendix B. Visualisations of conflicts

Conflict Trust-Trust

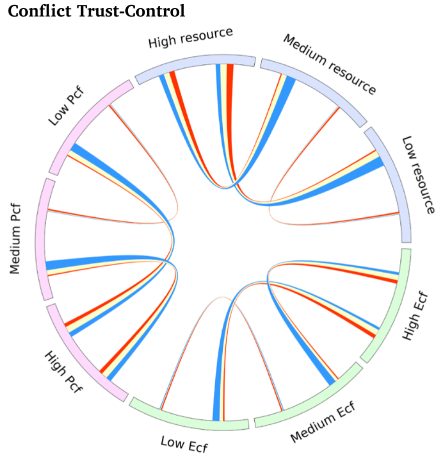


Capabilities: Trust v.s Trust

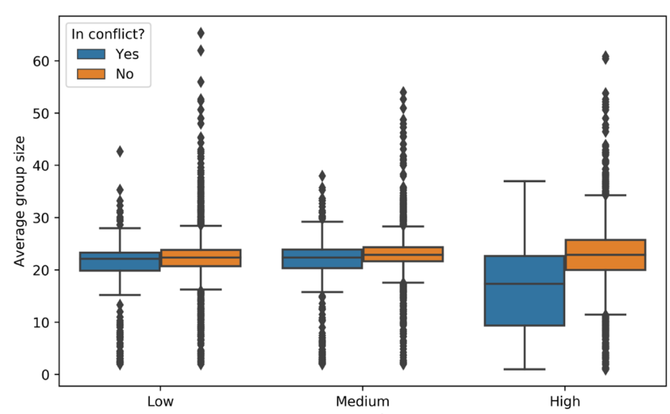


Capabilities: Trust vs. Trust

Conflict Trust-Control

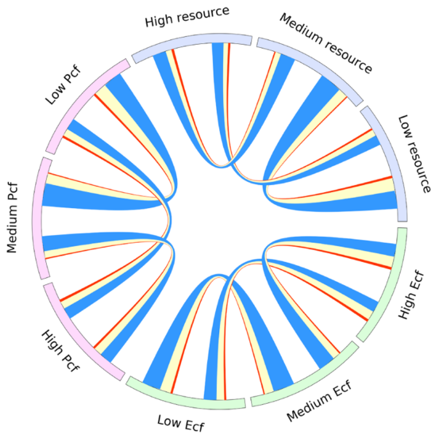


Capabilities: Trust v.s Control

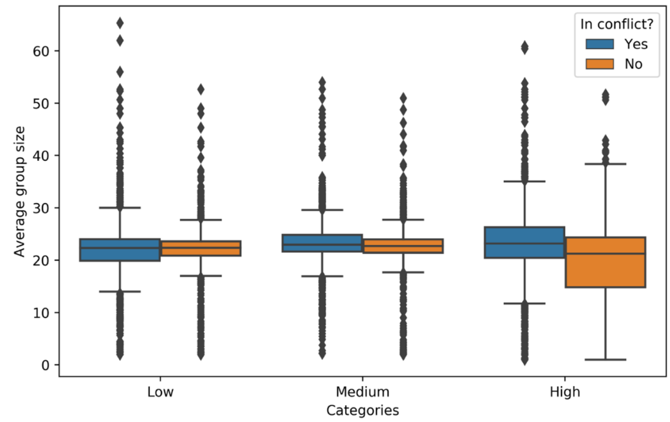


Capabilities: Trust vs. Control

Conflict Trust-Emotions

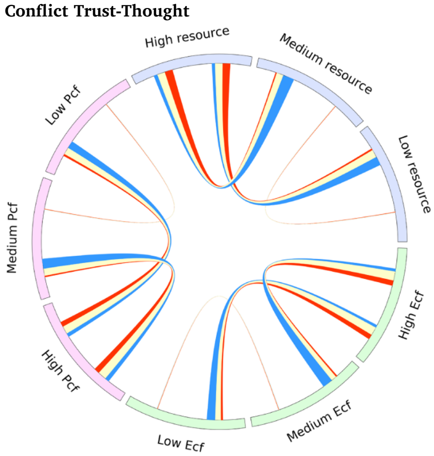


Capabilities: Trust v.s Emotions

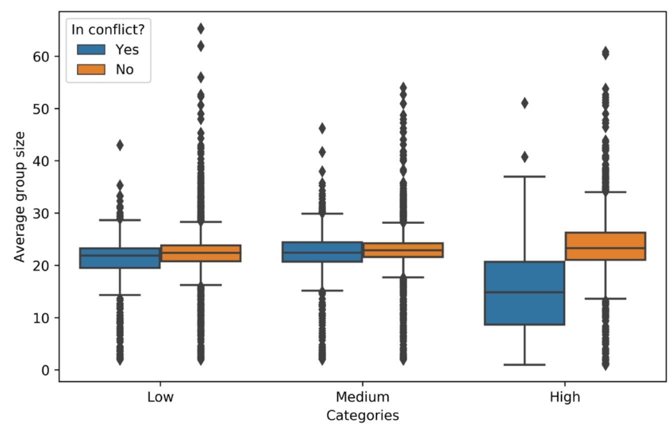


Capabilities: Trust vs. Emotions

Conflict Trust-Thought

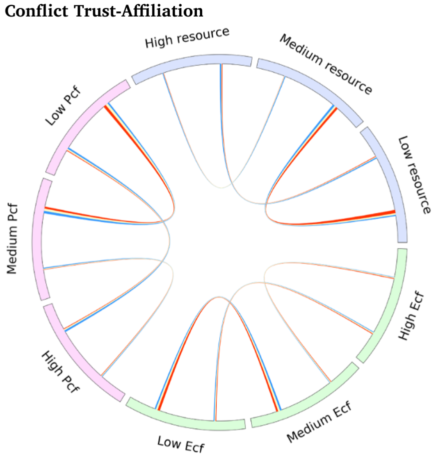


Capabilities: Trust v.s Thought

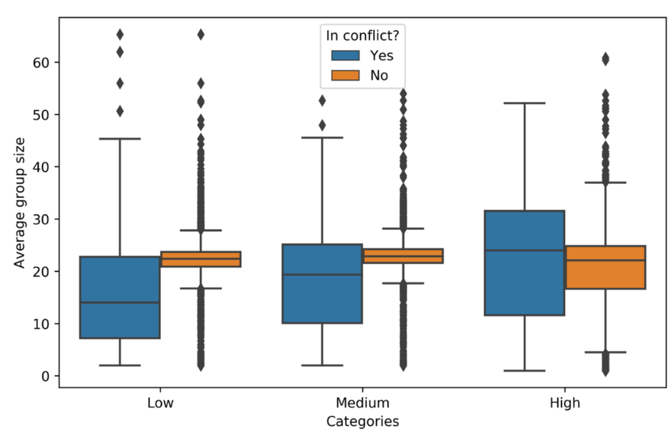


Capabilities: Trust vs. Thought

Conflict Trust-Affiliation

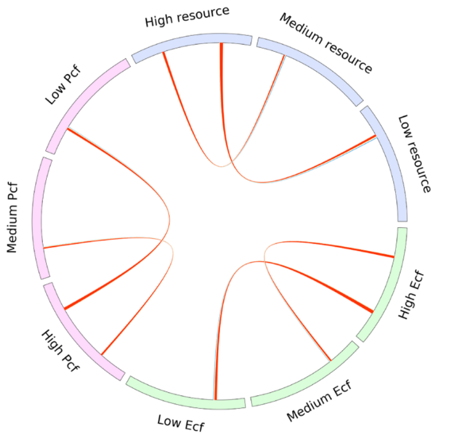


Capabilities: Trust v.s Affiliation

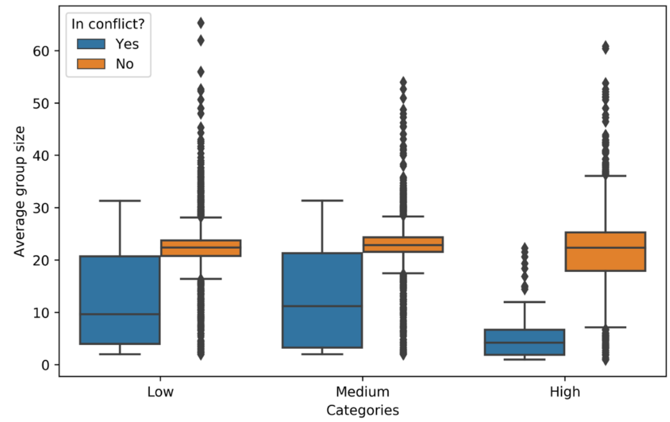


Capabilities: Trust vs. Affiliation

Conflict Control-Control

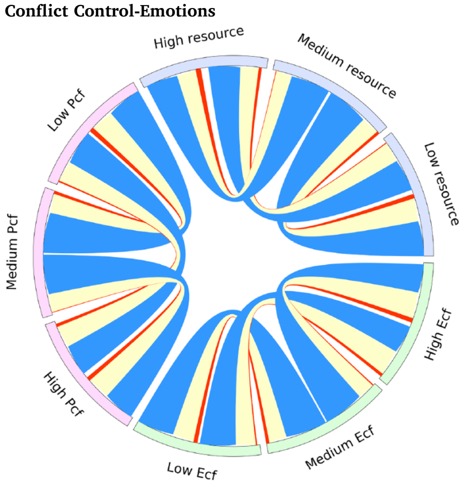


Capabilities: Control v.s Control

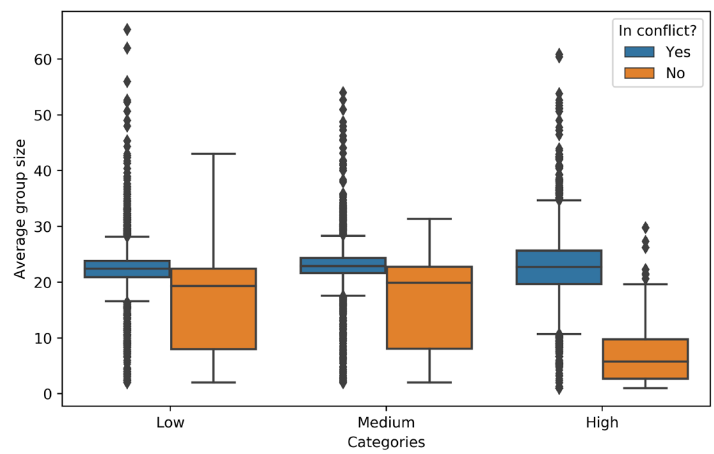


Capabilities: Control vs. Control

Conflict Control-Emotions

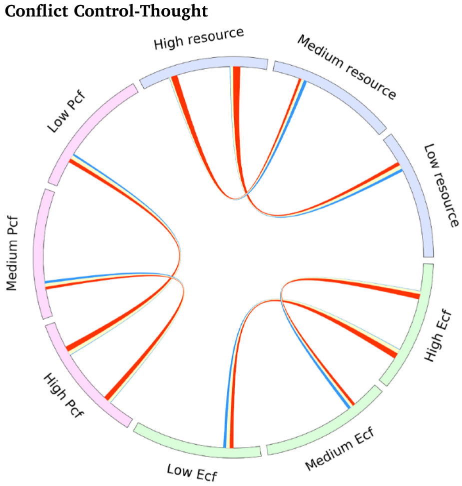


Capabilities: Control v.s Emotions

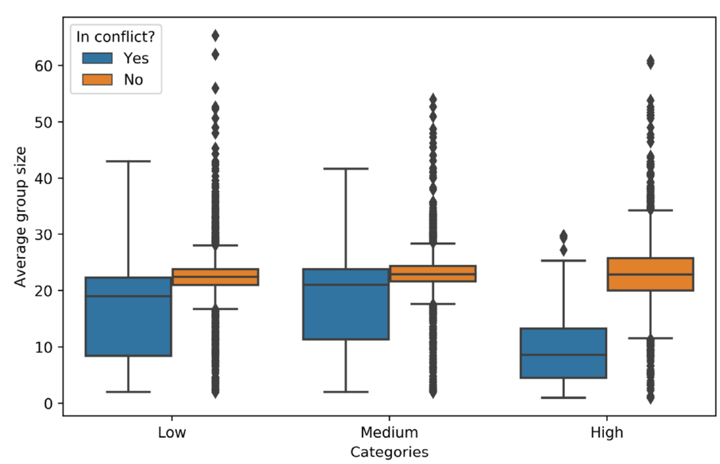


Capabilities: Control vs. Emotions

Conflict Control-Thought

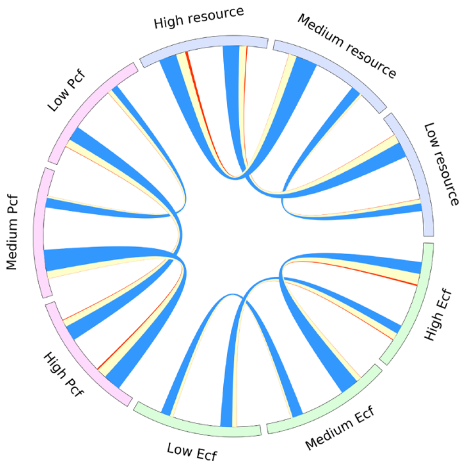


Capabilities: Control v.s Thought

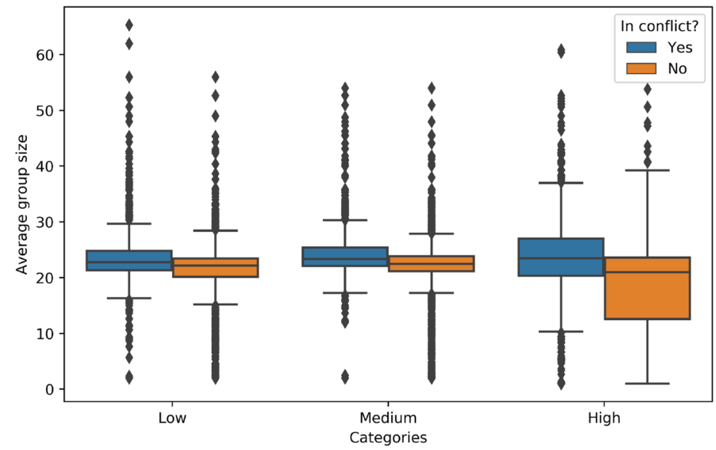


Capabilities: Control vs. Thought

Conflict Control-Affiliation

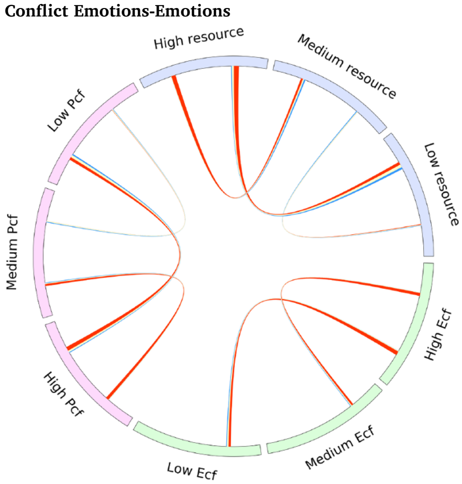


Capabilities: Control v.s Affiliation

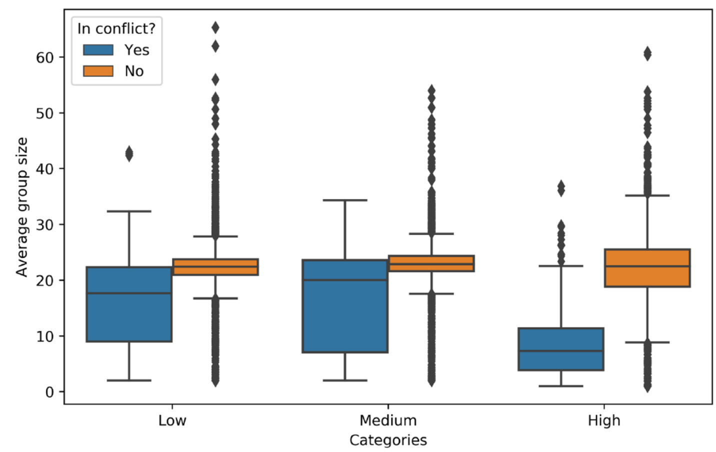


Capabilities: Control vs. Affiliation

Conflict Emotions-Emotions

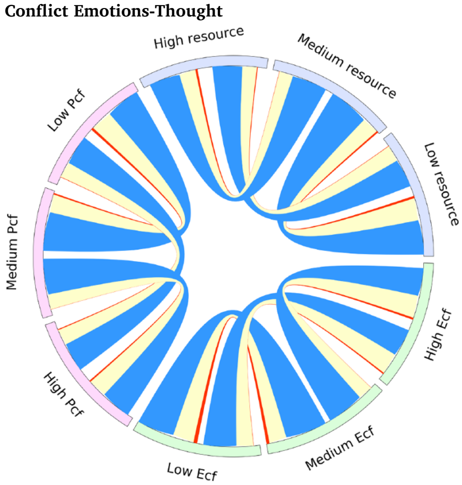


Capabilities: Emotions v.s Emotions

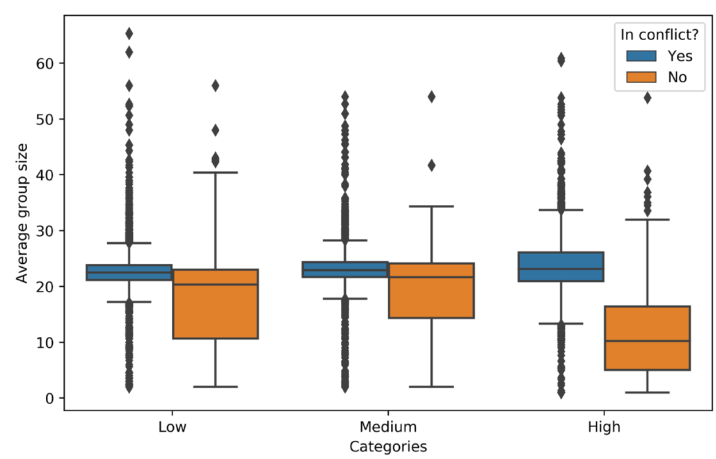


Capabilities: Emotions vs. Emotions

Conflict Emotions-Thought

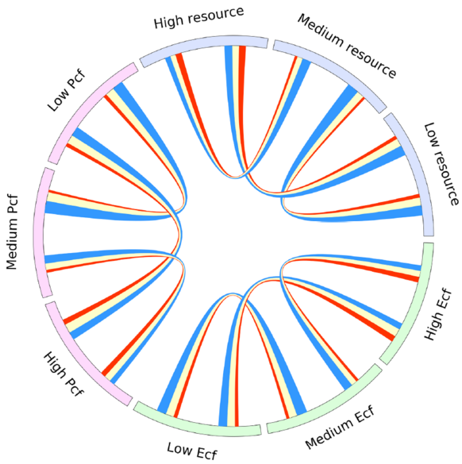


Capabilities: Emotions v.s Thought

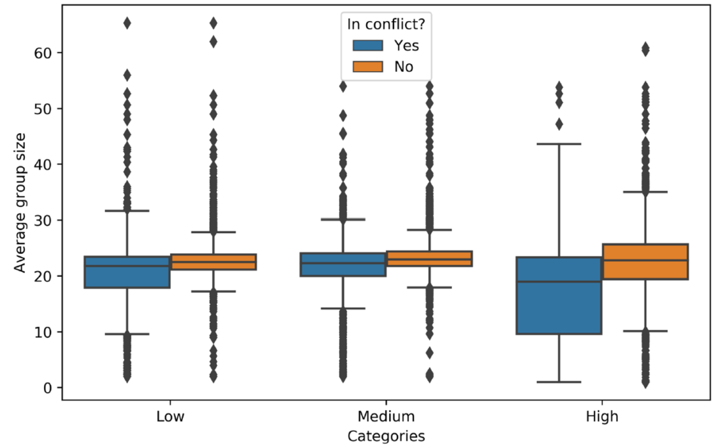


Capabilities: Emotions vs. Thought

Conflict Emotions-Affiliation

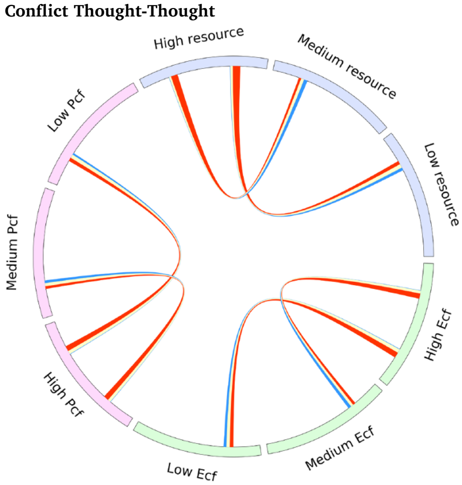


Capabilities: Emotions v.s Affiliation

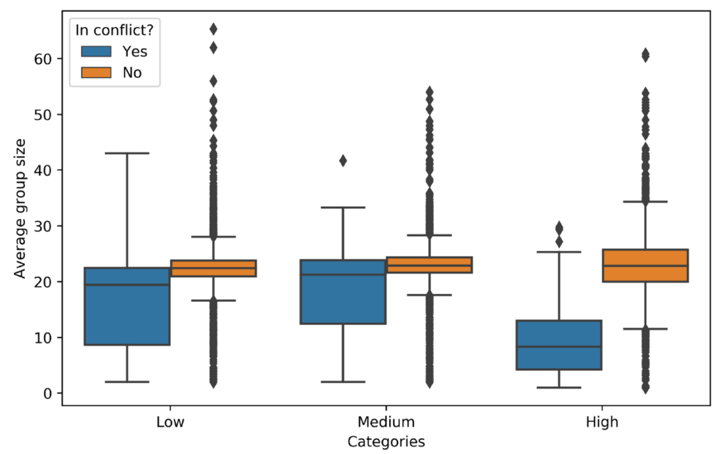


Capabilities: Emotions vs. Affiliation

Conflict Thought-Thought

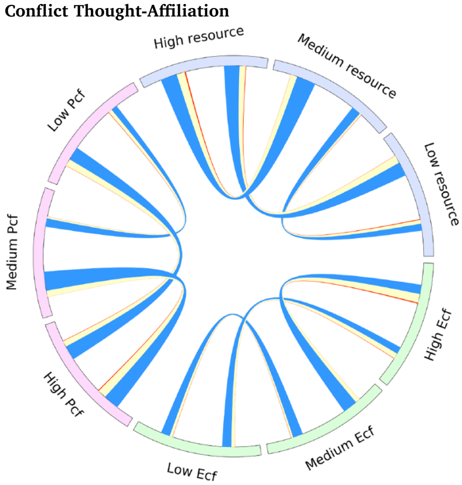


Capabilities: Thought v.s Thought

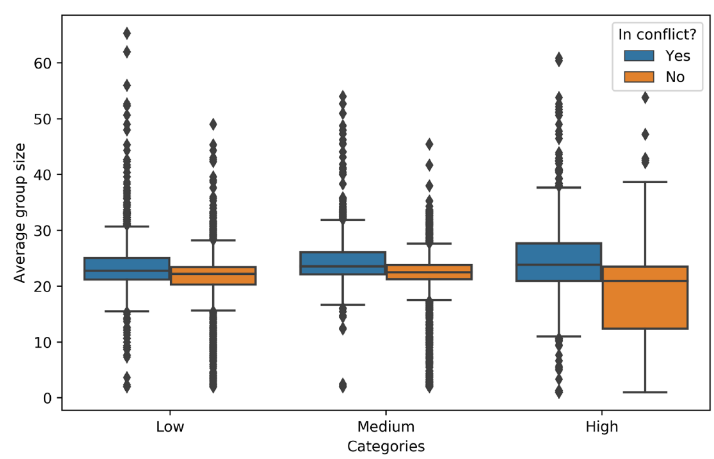


Capabilities: Thought vs. Thought

Conflict Thought-Affiliation

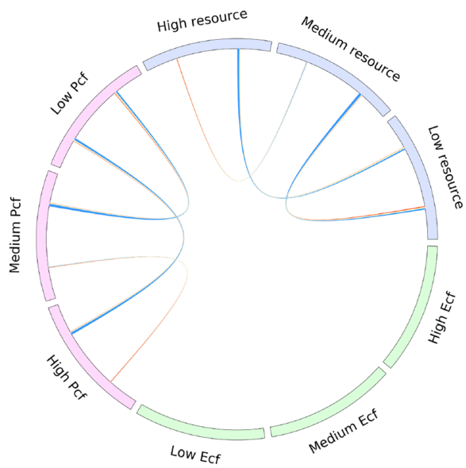


Capabilities: Thought v.s Affiliation

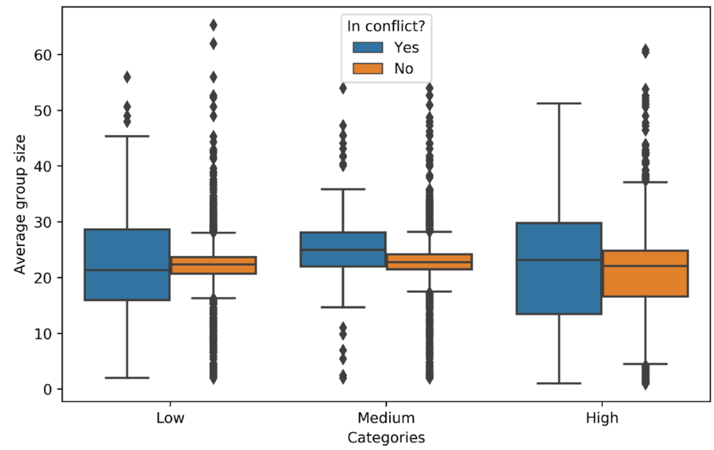


Capabilities: Thought vs. Affiliation

Conflict Affiliation-Affiliation



Capabilities: Affiliation v.s Affiliation



Capabilities: Affiliation vs. Affiliation

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